July 1947

# CHEMICAL COMPOSITION OF PLANTS AS AN INDEX OF THEIR NUTRITIONAL STATUS

by

D. W. GOODALL. Ph.D., D.I.C., F.L.S.

and

F. G. GREGORY, D.Sc., F.R.S.

*Price 9/-*

***TECHNICAL COMMUNICATION No. 17***

**IMPERIAL BUREAU OF HORTICULTURE AND PLANTATION CROPS**

Obtainable from I.A.B., Central Sales Branch, Penglais, Aberystwyth, Wales.

CABI BIOSCIENCE
EGHAM LIBRARY

CAB INTERNATIONAL
00090336

IMPERIAL BUREAU OF HORTICULTURE
AND PLANTATION CROPS,
EAST MALLING.

# IMPERIAL AGRICULTURAL BUREAUX

2, QUEEN ANNE'S GATE BUILDINGS, LONDON, S.W.1.

*Bureaux concerned with the cultivation of plants and allied subjects are :—*

IMPERIAL BUREAU OF AGRICULTURAL PARASITOLOGY (HELMINTHOLOGY),
Winches Farm, Hatfield Road, St. Albans, Herts.

IMPERIAL BUREAU OF PASTURES AND FORAGE CROPS,
Penglais, Aberystwyth.

IMPERIAL BUREAU OF PLANT BREEDING AND GENETICS,
School of Agriculture, Cambridge.

IMPERIAL BUREAU OF SOIL SCIENCE,
Rothamsted Experimental Station, Harpenden, Herts.

IMPERIAL FORESTRY BUREAU,
New Bodleian Building, Parks Road, Oxford.

AND

IMPERIAL BUREAU OF HORTICULTURE AND PLANTATION CROPS.

*Staff* :

| | | |
|---|---|---|
| *Consultant Director* | ..... | *R. G. Hatton, C.B.E., D.Sc., F.R.S.* |
| *Director* | ..... | D. AKENHEAD, M.A., B.Sc. |
| *Assistants* | ..... | H. WORMALD, D.Sc., A.R.C.S., D.I.C. |
| | | V. H. GOLDSCHMIDT, Ph.D. |

For list of publications of Imperial Agricultural Bureaux apply to I.A.B., Central Sales Branch, Penglais, Aberystwyth.

IMPERIAL BUREAU OF
HORTICULTURE AND PLANTATION CROPS

*TECHNICAL COMMUNICATION No. 17*

# CHEMICAL COMPOSITION OF PLANTS AS AN INDEX OF THEIR NUTRITIONAL STATUS

by

D. W. GOODALL, Ph.D., D.I.C., F.L.S.
The Research Institute of Plant Physiology, Imperial College of Science and Technology and the East Malling Research Station, and

F. G. GREGORY, D.Sc., F.R.S.
The Research Institute of Plant Physiology, Imperial College of Science and Technology

*Price* 9/-

Published by the **Imperial Bureau of Horticulture and Plantation Crops**, East Malling, Kent, England and obtainable from I.A.B., Central Sales Branch, Penglais, Aberystwyth, Wales

July, 1947.

# CHEMICAL COMPOSITION OF PLANTS AS AN INDEX OF THEIR NUTRITIONAL STATUS

## TABLE OF CONTENTS


| | PAGE |
|---|---|
| FOREWORD By Professor V. H. BLACKMAN, Sc.D., F.R.S. | 5 |
| INTRODUCTION : METHODS FOR THE DIAGNOSIS OF THE FERTILIZER REQUIREMENTS OF PLANTS | 7 |
| Field trials | 7 |
| Pot culture methods | 7 |
| Leaf painting and injection methods | 8 |
| Soil analysis : chemical methods | 8 |
| : biological methods | 9 |
| Neubauer and other seedling methods | 9 |
| by use of micro-organisms | 9 |
| Plant analysis methods | 10 |
| Use of deficiency symptoms | 10 |
| Other methods of nutritional diagnosis | 11 |
| HISTORICAL | 12 |
| Early work on diagnostic plant analysis | 12 |
| Recent work on diagnostic plant analysis | 19 |
| Identification of symptoms of nutritional disorders | 19 |
| Interpretation of the results of field trials | 41 |
| Determination of current nutrient requirements | 42 |
| Determination of soil nutrient status | 44 |
| THE AIM OF A METHOD OF DEFICIENCY DIAGNOSIS | 46 |
| THEORETICAL | 47 |
| Relation of yield to nutrient supply and uptake | 47 |
| Relation of internal nutrient concentration to nutrient supply | 49 |
| Relation of yield to internal nutrient concentration | 57 |
| Possible difficulties in the diagnostic use of plant analysis | 58 |
| SELECTION OF A TECHNIQUE | 61 |
| Selection of plants for sampling | 64 |
| Time of taking samples | 65 |
| Time of day | 65 |
| Time of year or stage of development | 65 |
| Organ of plant to be sampled | 67 |
| Preparation of material for analysis | 80 |
| Cleaning | 80 |
| Drying | 81 |
| Grinding | 81 |

PAGE

The analysis itself ..... 82
Determination of a nutrient other than that deficient ..... 82
Determination of the deficient nutrient ..... 82
Analysis for particular chemical fractions ..... 82
Nitrogen ..... 83
Phosphorus ..... 84
Sulphur ..... 84
Other elements ..... 85
Extraction methods ..... 85
Expressed sap ..... 85
Extraction by water ..... 86
Extraction by 2% acetic acid ..... 87
Extraction by sodium acetate buffer solution ..... 87
Extraction by hydrochloric acid ..... 87
Extraction by 1% sulphuric acid ..... 88
Extraction by ethyl alcohol ..... 88
Other methods of extraction ..... 88
Chemical and physico-chemical methods of nutrient determination in plant material ..... 89
Method of expression and interpretation of results ..... 89
Methods of expression of results of diagnostic analysis ..... 89
Results expressed per plant or per leaf ..... 90
Results expressed per unit leaf area ..... 91
Results expressed on a fresh weight basis ..... 91
Results expressed on a dry weight basis ..... 91
Results expressed on an ash basis ..... 92
Methods of interpretation of results of diagnostic analysis ..... 92
Interpretation based on percentage nutrient content ..... 92
Interpretation based on nutrient ratios ..... 107
Interpretation based on comparison of good and bad plants from the same field or plantation ..... 112
Factors affecting the use of plant analysis for deficiency diagnosis ..... 112
Weather conditions ..... 112
Pests and diseases ..... 113
Fixation of nutrients by the soil ..... 113
Variety ..... 113
Fruiting ..... 114

THE PLACE OF PLANT ANALYSIS AMONG OTHER METHODS OF NUTRITIONAL DIAGNOSIS ..... 115
Comparison of plant analysis with field trials as a diagnostic method ..... 115
Comparison of plant analysis with soil analysis as a diagnostic method ..... 116
Comparison of plant analysis with use of deficiency symptoms as a diagnostic method 116

BIBLIOGRAPHY ..... 118

SUBJECT INDEX ..... 156

AUTHOR INDEX ..... 162

# FOREWORD

" Timeliness and promise " have been claimed as proper tests of the value of a projected scheme of scientific investigation. To completed work a third test, that of performance, must be added. In this Technical Communication from the Bureau of Horticulture and Plantation Crops there is to be found not only timeliness, but also a promise of further benefit to agriculture following on performance.

A judgment of the mineral needs of a crop is a problem perennial in agriculture, so a memoir of this kind cannot fail of timeliness. A critical study of the plant-analysis method as a means to determine the mineral needs of the plants—and hence in the language of technology their " nutritional status "—is all the more timely when, as at the present day, the " trace " elements seem as important in plant nutrition as vitamins in the food of animals.

It can be claimed also that this memoir stands just as high by the test of performance. The various techniques of plant analysis have been widely used by many workers, but all too often a technique has been accepted without critical consideration, and on the analytical data obtained there have been based claims as to fertiliser treatment which cannot be substantiated.

In this communication the authors estimate the value of these plant analysis methods with all the critical, methodological apparatus of modern biological research. They also indicate by what techniques and in what circumstances valid results may be obtained. Furthermore, the reader will find the results of previous workers assembled here with a thoroughness which will excite the gratitude of all working in this field.

How heavy the task of compilation must have been is brought home to one by mere inspection of the huge tables (e.g., II, III and XII) with their hundreds of analytical data, and also by the author-index of over 800 entries.

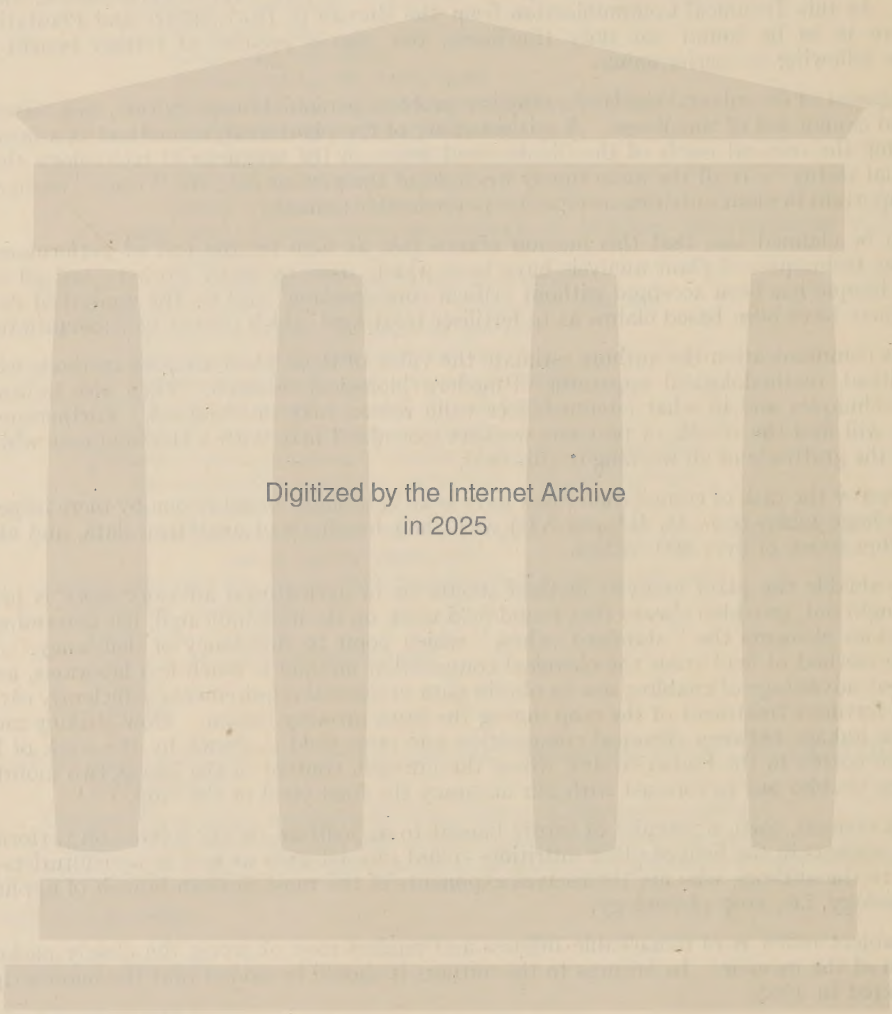
How valuable the plant analysis method should be in agricultural advisory work is here clearly brought out, provided always that sound field work, on the lines indicated, has determined for the various elements the " standard values " which point to sufficiency or deficiency. As against the method of field trials the chemical composition method is much less laborious, and has the great advantage of enabling one to obtain data of mineral requirements sufficiently early to allow of fertiliser treatment of the crop during the same growing season. How striking may be the close linkage between chemical composition and crop yield is shown by the work of F. Crowther on cotton in the Sudan Gezira, where the nitrogen content of the leaves two months after sowing enables one to forecast with fair accuracy the final yield of the crop.

In this memoir, then, a promise of future benefit to agriculture clearly follows on performance. All workers in the field of plant nutrition—plant physiologists as well as agriculturists—owe much to the authors, who are themselves exponents of the most modern branch of applied plant physiology, i.e., crop physiology.

The subject index is of remarkable fullness and renders easy of access the closely packed information of the memoir. In fairness to the authors it should be added that the manuscript was completed in 1945.

V. H. Blackman.

*February*, 1947.



Digitized by the Internet Archive
in 2025

https://archive.org/details/occasional-paper-imperial-bureau-of-horticulture_1947-07_17

# INTRODUCTION

## METHODS FOR THE DIAGNOSIS OF THE FERTILIZER REQUIREMENTS OF PLANTS

FROM the time of Liebig, the establishment of whether, in any particular instance, the amounts of nutrient elements absorbed by the plant from the medium in which it is growing are adequate to its needs has been a most important preoccupation of plant physiologists and agricultural chemists.

### FIELD TRIALS.

The most direct way of answering this question is, of course, to try the effect of additional amounts of nutrients, usually applied to the soil as artificial fertilizers, on the growth of the plants. Among the earliest of such experiments were the classical field trials at Rothamsted (Lawes and Gilbert, 1895), and these were followed by many others. It soon appeared, however, that generalizations could be drawn from the results of field experiments only with the greatest caution ; the effects of identical treatments on plant growth and yield varied greatly in different localities and seasons. In addition, field trials involved very considerable expenditure of time and money, and these considerations limited the utility of the method in practice. Nevertheless, in spite of the trouble and expense involved, and the uncertainty of generalizations drawn from them, field trials have during the past hundred years been set up on an ever-increasing scale ; there is no doubt that this will continue, whatever other methods for determining fertilizer requirements may be developed, for *at a particular situation and under given circumstances* the field trial represents the ultimate test to which the findings of any other proposed method must be submitted—if predictions founded on results of any other method fail to be confirmed by the results of field trials, such a method must be regarded as unsatisfactory.

### POT CULTURE METHODS.

As soon as the difficulties attending field trials became evident, the possibility was envisaged of conducting trials on a much smaller scale in pot culture, where the growth conditions other than those immediately concerned could be controlled to an extent impossible in the field. Pot culture experiments of this type have been set up wherever plant nutrition has been studied, and, especially in the form proposed by Mitscherlich (1925), their use has been adopted at certain European centres as a routine method for determining the fertilizer requirements of soils. The work of Mitscherlich and his school (as well as his critics) has been reviewed in detail by Stewart (1932) and Behrens (1935). Among other pot culture methods for the determination of fertilizer requirements may be mentioned those of Greisenegger and Vorbuchner (1918), Wiessmann (1927), Fraps (1912, 1931), McDonald (1933a), Gilbert and Pember (1935), Capo (1938), and Ferres and Trumble (1943). But all pot culture methods for nutritional diagnosis suffer from the fact that the volume of soil accessible to the roots of the plant in the pot is generally very much less than in the field, and that the structure and composition of the soil in the pot are also different. Consequently, results obtained in pot cultures can only be applied to conditions in the field with considerable reserve—and in fact it has often been found that responses of plants in pot culture to a treatment do not tally with responses to the same treatment in the field (Gerlach, 1926 ; Neubauer *et al.*, 1928 ; Schuster and Stephenson, 1940). Further, nutrients are absorbed from the materials present in the soil to various extents by different species, which prevents the results of a pot experiment (or, for that matter, of field trials) being applied directly to other species growing in the same soil.

## LEAF PAINTING AND INJECTION METHODS.

Another series of methods of nutritional diagnosis which may be regarded as bearing some relation to field and pot trials are those involving direct internal or external treatment with solutions of nutrients—by painting the leaves, or by the so-called solid and liquid injection techniques. These methods have been most widely applied in cases of chlorosis, where treatment with the deficient element causes the leaves to become green. In other instances the response may take the form of a local increase in size, or of a general increase in growth or yield. Painting methods have been mainly used for the diagnosis of iron deficiency (Gris, 1844 ; Gile, 1911 ; Parsche, 1936 ; Guest, 1943), but also for deficiencies of other trace elements (Bryan, 1929 ; Anderssen, 1932 ; Finch, 1933 ; Finch and Kinnison, 1933 ; Arnd and Hoffman, 1937 ; Chapman *et al*,. 1939 ; Chapman and Brown, 1941). Buslova (1939) and Roberts (1945a) have proposed a leaf-painting technique as a standard routine method. The diagnostic use of plant injection has been reviewed at length by Roach (1938, 1939 ; Roach and Roberts, 1945), who has put it forward as a routine diagnostic method.

The direct application of nutrients in this way has the advantage over soil application that no doubt arises that the materials reach the affected tissues ; in many cases also, results can be assessed in a much shorter time than after soil application. Their use, however, and in particular their interpretation, often demands considerable experience, and the results (especially of the smaller-scale methods) are very variable. In most cases where the methods have been successfully applied in practice, the deficiency has been sufficiently grave to cause marked symptoms ; whether they can be used to specify the fertilizer requirements of plants shewing only slight or no symptoms is still unproven.

## SOIL ANALYSIS : CHEMICAL METHODS.

The difficulties early found to attend field experimentation led to attempts almost contemporaneously with the inception of the Rothamsted trials to circumvent this troublesome method (except occasionally for control purposes) by the very much simpler expedient of finding directly the amounts of nutrients present in any given field soil. But it was very early found that the different forms in which the nutrients occurred in the soil could be absorbed by a plant with different degrees of facility, and some forms could not be absorbed at all ; this led to the concept of " availability" of soil nutrients to the plant.

The nutrient elements in manures or fertilizers added to the soil were often found not to be immediately or completely ' available' to the plant—frequently only a small proportion of the added nutrients was actually taken up.

Over the next few decades, the main attention of those studying this problem was devoted to improving methods of soil analysis and testing different methods for extracting the "available" fraction of the nutrients. A number of trials were carried out with solutions of carbon dioxide, since this was thought to be the means by which roots were able to absorb insoluble constituents, but more satisfactory results were obtained with other weak acids. Some of these procedures, and others involving the determination of " exchangeable" bases adsorbed on the surface of colloidal soil particles were found to give results in very tolerable agreement with the results of field trials. These remarks, however, apply in the main only to determinations of phosphorus and potassium ; methods for determining "available" nitrogen supplies in the soil have never met with general acceptance on account of the importance of nitrification in the soil, and techniques proposed for determining the "available" soil supplies of the trace elements are as yet in a very early stage of development. A number of textbooks are available dealing *in extenso* with the many methods of determining chemically those fractions of soil nutrients thought to be of importance to plant development (Behrens, 1935 ; Wright, 1939 ; Piper, 1942a), so the subject need not be discussed further here.

The subject of chemical soil analysis should not, however, be left without mention of the recent attempts to develop rapid systems of soil tests, many of which can be performed in the field (Thornton *et al*., 1934 ; Morgan, 1935, 1939 ; Hester *et al*., 1937 ; Anderson and Noble, 1937 ; Spurway, 1938 ; Baver and Bruner, 1939 ; Merkle, 1939 ; Purvis and Blume, 1941).

## SOIL ANALYSIS : BIOLOGICAL METHODS.

The progress made with chemical soil analysis over the past quarter of a century has not led agricultural chemists to become less aware that attempts to imitate the action of plant roots by chemical extractants can never hope to meet with full success—that working approximations are the most that can be expected. This has led many investigators to consider the possibility of using biological means of extraction.

### Neubauer and Other Seedling Methods.

It was from this point of view that early investigators of plant analysis as a means of determining fertilizer requirements set out. Their ideas will be discussed in greater detail in the following section, but they never achieved widespread acceptance among their contemporaries, and it was not until the nineteen-twenties that biological methods of soil analysis came to be widely used. The first of these was one bearing the name of Neubauer—which has certain resemblances to that proposed much earlier by Wilfarth (1897); this method, originally described in 1923 (Neubauer, 1923 ; Neubauer and Schneider, 1923), has been discussed in detail by Stewart (1932) and Behrens (1935) and consists in growing rye seedlings on a limited quantity of the soil in question under controlled conditions for eighteen days. The soil is then considered to have been exhausted of nutrients ; the seedlings are analysed for potassium and phosphorus, and the quantities found in excess of those in seedlings grown in pure sand, expressed in milligrams, are taken to represent the amounts of these nutrients available to the plant (" *wurzellöslich* ") in the weight of soil used. Limiting figures for root-soluble nutrients are laid down for each crop species and the extent to which the amounts extracted fall below these limiting values indicates the need for fertilizer applications. The method attained very widespread acceptance in Germany and other European countries, but though it has been tested several times in the United States (Thornton, 1931, 1931a ; Pettinger and Thornton, 1934 ; Stewart *et al.*, 1932) it has never been extensively used ; the reason, doubtless, is that its potential advantages over chemical methods of soil analysis were not considered to outweigh the troublesome amount of manipulation entailed.

The question might be raised whether the Neubauer method, as a method involving the analysis of plant material, should not be discussed at length in the body of this communication, instead of thus cursorily in the introduction. However, as Stewart (1932) writes, " it is in reality very little different from any purely chemical method of determining availabilities" ; in almost all the methods to be described in later sections, diagnosis is based on the *concentration* of the nutrients in the plant tissue, not on their total amounts ; and in most the plants providing analytical material have not been grown specially for the purpose, but form part of a normal field crop.

Other workers have developed modifications of the Neubauer method using wheat seedlings (Ames and Gerdel, 1927) or even tree seedlings (for forest soils) instead of rye. Süchting's method (Süchting *et al.*, 1938 ; Süchting, 1939, 1942) with tree seedlings also deviates from Neubauer's technique in that the plants are grown for a whole season and—as also in the work of Ames and Gerdel—account is taken not only of the total amount of nutrients taken up, but also of their percentage in the plant dry matter.

### By use of micro-organisms

Yet other biological methods of soil analysis have involved growing micro-organisms on the soil in question. A good account of work in this direction is given by Behrens (1935, 1937). Some of these methods display a certain affinity to that of Mitscherlich since it is on the growth rate of the test organisms that the conclusions are based, but they are all conveniently mentioned together here. The organisms used have included *Azotobacter* (Christensen, 1906, 1911, 1914, 1922 ; Niklas and Hirschberger, 1924 ; Truffaut and Bezssonoff, 1927 ; Winogradsky, 1928), *Bacterium globiforme* (Nicol, 1939) ; *Aspergillus niger* (Butkevič, 1909 ; Kosceleckiĭ, 1909 ; Benecke and Söding, 1927 ; Niklas *et al.*, 1930, 1930a ; Simakova and Bovschik, 1932 ; Sekera and Schober, 1934 ; Mehlich *et al.*, 1935 ; Sartory *et al.*, 1935 ; Mulder, 1938 ; Acock, 1941) ; *Rhizopus* (Seidel, 1931) ; *Cunninghamella* (Mehlich *et al.*, 1934) ; and algae (Morgan, 1933).

Comparative tests (Dirks and Scheffer, 1928 ; Mehlich *et al.*, 1933 ; Scurti, 1940) have not generally shewn any marked superiority of the biological methods of soil analysis over the better chemical methods. There are, however, certain disadvantages common to all methods of soil analysis, whether biological or chemical, when used to determine fertilizer requirements. These rest on the fact that they cannot, as indicated above, reproduce the conditions under which the plant growing in the field absorbs nutrients from the soil. This applies with especial force when it is desired to assess the nutritional conditions in a soil to which localized applications of fertilizer have been made—by a combine drill, for instance, or by band placement. The difficulties in the use of soil analysis in relation to nitrogen and the trace elements have already been mentioned.

## PLANT ANALYSIS METHODS

Reference has already been made to the analysis of plants growing in the field as a biological method of soil analysis. But plant analysis has relevance in a rather different respect to our central problem—the determination of fertilizer requirements. For if it can be shewn that the composition of a plant indicates its nutrient uptake or its nutrient needs —irrespective of the nutrient supplies in the soil—there becomes available a much more direct method than any technique for determining the " available " nutrients of the soil—which can be of interest only indirectly. It has in fact often been claimed that the composition of the plant does reflect its nutritional status—the adequacy of its nutrient supplies and the probability of its response to increased supplies. The examination of these claims will be the principal topic of later pages.

## USE OF DEFICIENCY SYMPTOMS

The last group of methods of nutritional diagnosis which have been widely used are those based on abnormal development of the plant when nutrition is unsatisfactory. This abnormal development takes many forms of which the most common are chlorosis and necrosis of the leaves. It often happens, however, that the symptoms of a nutritional disorder are characteristic enough to be recognized with some certainty, and several atlases of plates (Hambidge, 1941 ; Chilean Nitrate Educ. Bur., 1941 ; Wallace, 1943, 1944) have been published shewing the symptoms produced by deficiency or excess of different elements in different species of crop plants. The recognition of a definite syndrome resulting from a particular nutritional disorder has been a principal contribution of the method of water culture to nutritional diagnosis. In general, the intention has been that such symptoms should be recognized as and when they occur in plants grown in the course of normal agricultural or horticultural practice. The suggestion has been made, however, that small plots of plants specially susceptible to particular deficiencies should be planted specifically for this purpose ; such plants are described as indicators (Jones, 1929 ; Piper, 1940 ; Wallace, 1943, 1943a ; Reeve *et al.*, 1944). As a means of assessing the boron status of soils, the growing of sunflowers in pots under controlled conditions has been suggested, the time needed for the appearance of symptoms being taken as an inverse measure of the boron supply in the soil (Colwell and Baker, 1939 ; Schuster and Stephenson, 1940 ; Colwell, 1943). Others have suggested the observation of symptoms on common weeds—those of potassium deficiency on charlock, for instance (M. N. Nicholson, private communication)—as an indication of the fertilizer requirements of crop plants.

Where a disorder can be diagnosed on the sole basis of symptoms occurring in the field, this is obviously a very quick and cheap method of ascertaining the plants' needs.

But the type of symptom induced by a nutrient deficiency varies from species to species, and sometimes even from variety to variety (Wallace, 1943 ; Hill and Johnston, 1940 ; Boynton *et al.*, 1941 ; Lineberry and Burkhart, 1944), and may be affected by the supply of other elements (Richards, 1944). Moreover, different disorders may give similar symptoms (Eaton, S. V., 1935 ; Nightingale, 1937; Boresch, 1938 ; Chapman *et al.*, 1939 ; Chapman and Brown, 1941, 1941a, 1942 ; Wallace, 1943 ; Boynton *et al.*, 1943 ; Bathurst, 1944 ; Drosdoff and Kenworthy, 1944), or the symptoms of a nutritional disorder may resemble those produced by some quite different cause (Haas, 1937 ; Spencer and Lavin, 1939 ; Shear and Ussery, 1940 ; Gardiner, 1940 ; Hoffer, in Hambidge, 1941 ; Burkhart, 1941 ; Wallace, 1943). Consequently the method

demands a high level of discrimination, and sometimes confirmation by other techniques. Another limitation to the value of symptoms as diagnostic indices lies in the fact that they usually indicate only the most severe deficiency—the effects of inadequate supply of other nutrients are masked (McMurtrey, in Hambidge, 1941). Further, it has fairly often been found that nutritional deficiencies may cause diminutions in yield without inducing any other symptoms (Mitchell, 1934 ; Arnd and Hoffmann, 1937 ; Berger and Truog, 1939, 1940 ; Roach, 1940 ; Batjer and Degman, 1940 ; Burkhart, 1941 ; Ulrich, 1943 ; Hill, 1943) ; this suggests that a more sensitive method than the observation of symptoms may often be required.

## OTHER METHODS OF NUTRITIONAL DIAGNOSIS

Among other methods of deficiency diagnosis which have been tentatively investigated may be mentioned the work on absorption of nutrients from solutions by isolated discs of leaf tissue (Emp. Cott. Gr. Corp., 1942, 1943) and by seedlings transplanted from the soil under investigation (Lazurskiĭ, 1939, 1940). These methods are attractive from the theoretical point of view, but would be difficult to apply on a large scale in practice.

Ecologists have from time to time suggested the botanical composition of the natural or weed flora as an index of the nutritional conditions prevailing in the soil on which it grows (Müller, 1915 ; Rademacher, 1935 ; Walsh, 1942 ; Gdnrs' Chron., 1942). In particular, the presence of calcifuge species such as *Scleranthus annuus* and *Rumex acetosella* has been proposed as an indication of the necessity of liming (Christensen and Larsen, 1910 ; Eichinger, 1929). While the general dependence of the distribution of species on nutrient supplies may be accepted, rarely is the effect clear enough to be practically useful ; this principle seems, however, to have found some application in identifying those areas in the United States where the amounts of selenium in the soil were high enough to cause danger of toxic effects in mammals (Byers *et al.*, 1938 ; Beath *et al.*, 1939)—such areas seem to be characterized by the presence of certain species of *Xylorrhiza, Stanleya, Oonopsis* and *Astragalus*.

The fact that nitrogen deficiency is usually characterized by a pale yellowish-green colour has led some workers (Gassner and Goeze, 1936 ; Borden, 1942) to suggest chlorophyll determinations as a means of assessing nitrogen requirements ; it is found, in fact, that a diminution in chlorophyll content can be shewn as a result of a degree of nitrogen deficiency not detectable by the appearance of the plant to the eye. Gassner and Goeze (1936) proposed a detailed technique for finding nitrogen requirements by chlorophyll determination which involved the growing of rye for 25-30 days in pots of soil and simultaneously in sand with different nitrogen supply levels. More recently, chlorophyll determinations have been recommended by Boynton and Compton (Boynton, 1945 ; Boynton and Compton, 1945 ; Compton and Boynton, 1945) for assessing the nitrogen status of apple trees.

This completes the introductory review of the different methods of assessing fertilizer requirements. A detailed consideration of the various methods which have been proposed making use of plant analysis will now be embarked upon, and later their value will be compared with that of the other techniques described above.

# HISTORICAL

## EARLY WORK ON DIAGNOSTIC PLANT ANALYSIS

Soon after the importance of the supply of nutrients from the soil for plant growth was recognized, and before the extent to which this supply varied in different soils was realized, the view was put forward, particularly by von Liebig (1840), that if soil fertility was to be maintained the quantities of nutrients removed from the soil in crops would need to be restored to it in the form of applications of manures or fertilizers (" Law of Restitution "). To apply this rule, it was necessary to know the average composition of the parts of crop plants harvested. But as knowledge on the varying response of different soils to different manurial materials accumulated, it became generally appreciated that, however true the " Law of Restitution " might ultimately be, it provided no guide whatever to the economic use of fertilizers.

The first investigator to have conceived the idea of using plant analysis as an index of available nutrient supplies appears to have been Weinhold (1862, 1864). He set out from the assumption that the plants growing naturally in any location in greatest abundance would be those whose nutrient needs the soil was best fitted to supply. Hence, these plants should contain nutrients in similar proportions to the assimilable nutrients of the soil, and the composition of the most abundant wild plants should provide information on the nutrient status of the soil. A corollary of this line of reasoning was that, when more than one species was abundant in a locality, all such species should be similar in nutrient composition. This was first tested (1862) on arable weeds, and found not to hold ; Weinhold considered that this might be due to the effects of cultivation on interspecific competition, and that plants growing on a virgin soil might agree better in composition. Later, however, (1864) he was able to test the hypothesis on the vegetation of a woodland soil ; though the agreement was better than for arable weeds, it was so far from satisfactory that Weinhold concluded that the physical properties of the soil were more important for plant competition than its chemical characteristics, and he abandoned this line of work.

Three years later, Hellriegel (1867) published the results of sand culture experiments with barley in which he found that the potassium content of both grain and straw increased with increasing potassium supply. He concluded : " In order to give a maximum yield, barley must be able to take up at least 5 parts of potash to every 1,000 parts of straw dry-matter and 3.8 to every 1,000 parts of grain dry-matter." The following year, at a conference of agricultural chemists, Hellriegel (1869) pointed out the disadvantages of chemical soil analysis, and suggested that analyses of harvested plant material might provide a better index of available nutrients in the soil; "if the necessary foundations are first laid by field trials, crop analysis will provide a satisfactory basis for the determination of both the relative and absolute proportions of plant nutrients present and available in the soil, and can suitably give the supplementary information needed to evaluate the results of soil analysis." Although his experimental work on the subject was slight, Hellriegel's ideas proved very stimulating to European investigators during the next three decades.

In 1868 also, as a result of an extensive series of water culture experiments with oats, Wolff was able to suggest 0.3% CaO as the minimum content of the whole aerial parts at maturity which corresponded to satisfactory growth. Subsequent work on the same lines (1876, 1877) enabled him to publish figures in respect of each of the six principal nutrients, not only the necessary minimal content (" *absolut nothwendige Minimum* ") being quoted, but also values for good average development. These figures are reproduced in Table XIV.

The next work in this field which it is necessary to note is that of Heinrich (1882). He objected to the work of Hellriegel (1869) on the grounds that whole plants had been analysed—which might be a cause of error if the proportions between the organs varied. He analysed for

nitrogen various parts of oats plants receiving high and low nitrogen supplies, and concluded " that the *roots* are the most appropriate organ for comparative investigations involving the determination of nutritional conditions in the soil," since " the roots at maturity are the more depleted the poorer the soil is. The whole of the available nutrients have migrated to the aerial parts of the plant, there to be used for assimilation and for the formation of new organs." The choice of roots was supported because their composition was thought to be less liable than that of the aerial parts to influence by extraneous factors ; and Heinrich found the average root composition to be little affected by the loss of fine roots in the course of washing. He propounded a " Law of the Minimum " to the effect that when the supply of a nutrient was limiting growth its concentration in the root tissue declined to a certain minimal value. Minimal percentages were laid down for the content of the six principal nutrient elements in the dry matter of oat roots at maturity (see Table VII), and if in a sample under investigation the content of an element was at the minimal level, that element was deficient ; if none of the nutrients was at the minimal level but the content of one approached more nearly to the minimal level than that of the others, the probability of a response was often indicated.

Heinrich's ideas were followed up by Haessner (1887) and von Dikow (1891). Haessner analysed the roots of barley plants from a fertilizer trial, but found only slight differences in composition ; this is perhaps hardly surprising since the fertilizer effects studied were *residual* effect of treatments applied to sugar beet during the previous year. von Dikow also investigated the composition of roots of barley plants receiving different fertilizer treatments in the field ; the " roots " referred to included parts of the plant below the " first node." Since the four plots receiving only nitrogen and phosphorus gave roots differing considerably in potassium content, it was considered that the minimum content for the latter element had not been reached, and no limiting value was quoted. The minimum for phosphorus was given as 0.13% $P_2O_5$ since three of the four plots receiving only nitrogen and potassium approximated to this figure ; and on similar grounds the minimum for nitrogen was given as 0.63%. The data did not indicate any " luxury consumption," such as was found by Heinrich, and von Dikow suggested that the range of mineral content of plant tissue was limited both above and below, and that Heinrich's " Law of the Minimum" should be supplemented by a " Law of the Maximum " ; until this maximum mineral content was attained, fertilizer applications did not have their maximum effect on plant growth.

Heinrich's proposed method was also tested by Helmkampf (1892) and by Stahl-Schröder (1904). Helmkampf analysed the roots of oats and wheat subjected to different manurial treatments ; the nitrogen content in all plots was close to Heinrich's minimal range-in agreement with the marked response to nitrate fertilizer ; the potassium content was increased by potassium supply, while the phosphorus content remained fairly constant at 0.40-0.48% $P_2O_5$ irrespective of phosphate fertilizer treatment, which was taken as indicating that the maximal value suggested by von Dikow had been reached. Stahl-Schröder carried out similar experiments, and agreed that root composition reflected the soil supply of nutrients ; weather conditions in different years were found to affect root composition considerably, but the potential value of the method in more extreme cases, especially where different fields on the same farm could be compared, was not doubted.

Unlike von Dikow and Helmkampf, Stahl-Schröder found abundant evidence of "luxury consumption," and rejected von Dikow's proposal of a "Law of the Maximum." He considered that von Dikow's results might be ascribed to excessive leaching during the washing of the roots. Both Helmkampf and Stahl-Schröder considered that the difficulties of preparing and washing the roots rendered them an unsatisfactory part of the plant to sample ; Stahl-Schröder moreover found that the fine roots, many of which were lost during removal from the soil and washing, differed considerably in composition from the coarse roots. Since both these workers had obtained satisfactory results with other parts of the plant (see below) they decided on these grounds to reject root analysis.

Shortly after the publication of Heinrich's work on oat roots, Atterberg (1886, 1887, 1887a, 1887b, 1888, 1888a, 1889, 1901) began a lengthy series of experiments in Sweden, both in sand culture and in the field. The crop plant used was again oats, but the various aerial organs and not the roots were analysed. As a result of these investigations he came to the conclusion that

analysis of the grain provided a better index of the nitrogen and phosphorus supply conditions than that of the straw, but that grain analysis was of little use in relation to potassium nutrition, since the content of potassium in the grain was small and varied little in accordance with changes in external supply. Accordingly, for determining the potassium status, analysis of straw was recommended, or of the whole tops of plants harvested at the flowering stage ; the latter material could also be used for nitrogen and phosphorus analyses ; on the other hand, the analysis of whole plants *at maturity* was deprecated, since results would be greatly affected by the varying proportion of grain and straw. In the grain a value of 1.6 to 1.7 for the ratio $\frac{N}{P_2O_5}$ was optimal, and if this ratio exceeded 2.0 phosphorus deficiency might be suspected unless the phosphorus content was above 0.9% $P_2O_5$ (1888a). For whole plants sampled at flowering time the optimal ratio was $N : P_2O_5 :: 100 : 45$ (1889). As regards potassium, provided the sodium content was high, yield began to suffer when the potassium content of the straw fell below 1.0% $K_2O$, and at a level of 0.37-0.38% deficiency symptoms appeared ; if the sodium content was low, potassium deficiency symptoms might appear with as much as 1.0% $K_2O$ (1888a). Atterberg also (1889) paid some attention to the ratio of nitrogen to potash—determined in the grain and straw respectively ; he considered that this ratio should not exceed unity (1889). Calcium deficiency symptoms (1901) appeared when the calcium content was in the range 0.10-0.18% CaO. The composition of the plants was found to be affected by water supply and by spacing.

Minimal and average figures were quoted for the content of the principal nutrients (see Table XII), but Atterberg did not accept the idea of a 'maximum' postulated by von Dikow (1891)—in fact he obtained some evidence (1888) that supra-optimal phosphorus supplies might continue to increase the phosphorus content of the plant even while they decreased the yield. The use of the minimal and average values he describes (1901) in this fashion : " Which nutrient is present in minimum may be determined in the following way : one compares the percentage nutrient contents found by analysis with the corresponding mean and minimum values for oats. The nutrient whose content is most below this mean, or exceeds it least, and approaches the minimum most closely, is in minimum." While plant analysis was considered to give better information on the nutritional status of the plant than soil analysis, it was recognized that the results of the former could not lead directly to conclusions on nutrient supplies available in the soil. Atterberg anticipated (1889), but apparently did not carry out, the extension of these methods to other crops.

Helmkampf (1892) tested Atterberg's proposed technique on material from the same manurial trial as that mentioned above in connection with his critical examination of Heinrich's method. He came to conclusions substantially in agreement with those of Atterberg, but considered analysis of the whole aerial part of the plant sampled at flowering time was the most promising procedure. Helmkampf did not accept the concept of " luxury consumption," and in accordance with this view regarded an increase in the nutrient content with fertilizer supply as a more important index of the need for that fertilizer treatment than the absolute level of the nutrient content. Januszewski (1895), in conformity with the results of Atterberg and Helmkampf, found analysis of wheat grain a useful index of the nutritional status of the plants. Stahl-Schröder (1904), too, tested Atterberg's proposed method and found treatments to have the expected effect on the $\frac{N}{P_2O_5}$ ratio in the grain, though the values found were considerably lower than those of Atterberg. This difference was ascribed to climatic differences between Peterhof and Kalmar, where the experiments of Stahl-Schröder and Atterberg respectively were carried out, and for the Peterhof region a ratio of 100 : 35-40 was regarded as satisfactory. The same climatic factors affected the $\frac{N \text{ in grain}}{K_2O \text{ in straw}}$ ratio, and for this values of the order of 100:75 were considered satisfactory in Kurland. The examination only of ratios between nutrients was not, however, thought adequate ; attention should also be paid to the absolute nutrient content values. Stahl-Schröder expressed the view that more attention should be paid to data from straw analyses ; but it was in the more extreme cases that plant analysis was likely to be most useful, and conclusions that an element was in adequate supply were thought in general to carry

a greater degree of certainty than conclusions that it was deficient—since many irrelevant factors might interfere with the uptake of a nutrient and cause apparent deficiency. He reported the results of a survey of the nutritional status of crops in Kurland carried out by plant analysis, and gave some instances where the results proved to be of practical value. He claimed that the results obtained with oats would generally apply also to other crops. Stahl-Schröder objected to Helmkampf's suggestion that the whole aerial parts should be sampled at flowering time on the grounds that it would not be easy to gather samples from a number of different sites at just the same stage of development, and even slight variation in the stage at which sampling took place might well be reflected in a difference in composition.

Joulie (1889) gave an account of a case where poorly-cropping land had been brought into excellent heart by combining the diagnostic use of plant and soil analysis. The original fertilizer régime was decided on a basis of the results of soil analysis ; the crops grown subsequently were analysed, the values were compared with "*compositions types*" (averages of numerous data from plants of good growth), and nutritional deficiencies thus made apparent were remedied.

von Seelhorst (Liebscher *et al.*, 1898) reported an experiment in which oats were grown in pot culture on twenty-four soils, each receiving eight different fertilizer treatments. The plants were harvested just before the milk-ripe stage ; their dry weights were determined and the material was analysed for nitrogen, phosphorus and potassium. The plant composition was found to be reasonably closely correlated with the fertilizer responses shewn in dry matter yield. Nutrient percentages in the plant material indicating that adequate supplies were available were deduced (Table XII), but it was emphasized that fertilizer responses could not be predicted from the percentage of one nutrient alone ; for instance, a value for nitrogen content indicating the probability of a definite response to applications of a nitrogen-containing fertilizer, when supplies of other nutrients were fully adequate, would be associated with no such response if either potassium or phosphorus was in short supply. von Seelhorst concluded that under controlled growth conditions plant analysis could be used to determine fertilizer requirements and was more reliable than soil analysis ; he pointed out, however, that conditions in pot culture were very different from those in the field. However, as part of the same scheme of work, an extensive series of field trials was also reported (Edler, 1898), many of which appear to have been at the same sites from which soil was collected for the pot culture experiments ; though Von Seelhorst did not comment on this aspect of the work, there appears to be a moderate degree of correlation between the responses observed in the field trials—both with oats and potatoes—and the composition of the oat plants from the untreated pots.

Godlewski (1901) criticised the experiments reported by von Seelhorst on the grounds that the plants were grown in pot culture, and reported results from some field fertilizer trials carried out on wheat, barley and potato. From the wheat experiment samples were taken at flowering time, while for the other two crops the final harvested material was analysed—grain and straw, or tubers. From the potato tuber analysis, it was concluded that nitrogen was deficient if the the ratio $\frac{N}{P_2O_5}$ was less than 2, or $\frac{N}{K_2O}$ less than 0.6 ; when the potassium nutrition was inadequate, the ratio $\frac{K_2O}{P_2O_5}$ was less than 2.5 Similar limiting values (Table XV) were also quoted for the nutrient ratios in barley straw, which Godlewski regarded as more suitable than the grain : " This relationship is particularly evident in the composition of the straw ; it is much less clear in that of the grain" In barley the ratio of nitrogen to the metallic nutrients was not thought to be of any importance. Hanamann (1904) also performed some analyses on barley plants subjected to various fertilizer treatments in pot culture and in the field. Root and grain analyses were not considered promising but the composition of the mature straw and of the whole tops sampled after flowering provided useful indications of fertilizer requirements.

Influenced by the original work of Hellriegel, Nanninga (1903, 1904) at Buitenzorg was led to study quite a different crop—tea. From a study of the composition of the ash of the tea leaf, he concluded that in general ash analysis would shew which elements were in inadequate supply in a poorly-cropping plantation. Since, however, he found no connection between the potassium content of the ash in the samples he studied and that of the soil, he concluded that in the

tea gardens of Java potassium was never in minimum. Leaf analysis was considered both quicker and more trustworthy than soil analysis as an index of mineral deficiencies. Remy (1903, 1903a, 1903b) considered the possibility of using leaf analysis to indicate the fertilizer needs of hops. From a few analytical results in fertilizer trials, he concluded that in respect of nitrogen and phosphorus, though not potassium, " the chemical composition of senescent leaves gathered at a particular level gives information on the fertilizer status of the soil". He chose the senescent leaves on *a priori* grounds, since under deficiency conditions they were depleted of nutrients to meet the needs of the regions of active growth. Limiting values (see Table VIII) for phosphorus content of these leaves were suggested (1903b). Schneider (1905) later confirmed that the differences in composition of the oldest leaves with different treatment were in fact more marked than in other parts in June, though later in the season rather younger leaves were to be preferred. Later, Remy turned his attention to other plants, and (1906) shewed that the same principle applied to oats—that differences in phosphorus nutrition were more evident in the composition of the older leaves and stems than in the growing regions. In apple trees (1906a), the leaves were again suitable organs to analyse for the purpose of indicating nutritional requirements.

Up to this time, all the work on this subject except that of Nanninga had been performed in continental Europe ; but in 1905 Hall, then Director of Rothamsted Experimental Station, intervened in the discussion. He drew data mainly from analysis of harvested products from the long-standing field manurial trials at Rothamsted—grain and straw of wheat and barley, tubers of potatoes and roots of mangels. He found that differences in the composition of the plant ash with treatment were less marked than those in available nutrients in the soil ; also the composition of the plant ash was subject to considerable seasonal variations. Of the materials mentioned, the only ones considered promising were barley straw, the ash of which shewed marked variations in potassium and phosphorus content with treatment, and—for potassium determinations—mangel roots. In another experiment, oats were grown in pot culture in six soils whose responses in the field to fertilizers were known ; the plants were harvested before maturity, and the potassium and phosphorus content of their ash was found to be lowest on the soils responding to the respective fertilizers ; but replicate pots shewed considerable variation in ash composition. Hall made some further observations on a series of eight fertilizer trials with swedes in different parts of England, and found the composition of the ash of roots from the untreated plots to be closely related to the observed response to fertilizer treatment. Even here, however, he did not consider that plant analysis would prove more useful than soil analysis. He concluded by expressing the view that to use analysis of crop plants as a method for determining fertilizer needs it would be necessary to set up special unmanured plots growing the plant in question ; therefore, " some test plant must be found which grows pretty universally on all soils, in fact some weed of arable land that would always be available. . . . It is in the direction of finding such a test plant that I am now continuing the work." It does not appear, however, that Hall ever published any reports of his experiments on weed analysis, and—apart from a hint by Haddock (1934) in regard to *Chenopodium album* and magnesium deficiency and some negative results in Australia (Teakle, Thomas and Turton, 1941) on the possibility of using capeweed to indicate copper deficiency—this possibility seems to have remained uninvestigated until the work of Goodall (1945c) shewing that the potassium content of *Polygonum convolvolus* leaves may indicate the potassium requirements of barley.

Hall's paper appears to have had a discouraging effect, for the volume of work published on plant analysis as a diagnostic procedure declined markedly during the next two decades. Probably the development of improved methods of soil analysis was also in part responsible for this decline. But work on plant analysis for determining fertilizer requirements continued at Darmstadt and Breslau, and in Switzerland, and Jakuškin (1915) in Russia published an isolated investigation on phosphorus deficiency in cereals.

In 1907 Wagner and his collaborators described a series of fertilizer experiments with grape vines ; in a set of long-term pot cultures, under different manurial treatments, the leaves and wood, and the juice and pulp of the fruit were analysed for nitrogen, phosphorus and potassium. It was found that analysis of the leaves shewed fertilizer differences better than that of the other parts. In healthy plants, it was stated, the leaves contained some 1.56% nitrogen, 1.24%

$K_2O$ and 0.43% $P_2O_5$ ; vines with mineral content above this level would shew no response to fertilizer treatment. Later work (Wagner, 1911, 1924) led only to very small modifications in these figures. It was pointed out that the fruiting condition of the vine would affect the composition of the leaves—especially their potassium content—and that none of the three nutrients could be considered in isolation.

In 1875, Emmerling had mentioned a case where soil analysis had been supplemented by analysis of hay for the purpose of diagnosing the cause of unsatisfactory growth in a meadow, and making fertilizer recommendations ; this work does not appear to have been continued, but in 1909 Wagner reported the results of fifteen field experiments on the manuring of meadows, extending over several years ; he found that the potassium and phosphorus content of the hay varied greatly with the treatment, and was able to propose values for its percentage composition characteristic of different levels of adequacy of nutrient supply (Table IX). Subsequent work (Wagner, 1921) did not necessitate any alteration in these characteristic values. He considered the comparison of hay analyses with these characteristic values to be a very useful substitute for field fertilizer trials where the latter were impracticable. Wagner's proposals had to meet a certain amount of criticism (Remy, 1911 ; Stutzer, 1914 ; Haselhoff, 1918), but aroused considerable interest. Tacke (1910, 1910a, 1910b) found that Wagner's characteristic values applied satisfactorily to hay from German bogs and marshes, but von Feilitzen (1910, 1910a) considered that they were too high for conditions in Sweden. Müller (1915) in Switzerland tested Wagner's conclusions on samples from a series of nine fertilizer trials in different parts of the country and concluded that this method might even be more trustworthy than field trials. Liechti and Ritter (1917) also carried out an investigation on similar lines, as a result of which they proposed modifications in Wagner's characteristic values to meet Swiss conditions. Like Müller, they considered that the exact stage of development reached at the time of harvest would affect the composition of the hay ; they also suggested that its chemical composition would to some extent depend upon the proportion of different species present. Mayr and Ahr (1919), in a careful critical study of the method, while regarding Wagner's general conclusions as confirmed by their work, considered that the botanical as well as the chemical composition of the hay should be taken into account. This point was the subject of several other criticisms of the method in later years (Raum, 1926 ; Kauter, 1935 ; Truninger and von Grünigen, 1935). Alway *et al.* (1926), in a series of fertilizer trials on ten clover-timothy fields, were unable to shew any relationship between the phosphorus content of the hay and the response to phosphate fertilizers. Nevertheless, hay analysis continued to be used extensively in Switzerland as a basis for fertilizer recommendations for grassland, with very satisfactory practical results (Wiegner, 1933). It has also been used in Holland (van Itallie, 1935 ; Hart and van der Paauw, 1942).

Wagner (1915) also reported the results of a very extensive series of rotational fertilizer experiments with field crops, and on this basis proposed the analysis of cereal straw, roots of beets, or tubers of potatoes as a means of characterizing the fertilizer requirements of arable soils. The limiting values he mentioned are cited in Table XII. Hoffman (1917) tested this possibility in regard to the potassium content of cereal straw, and concluded that the value of such a diagnostic technique was much less well established than in regard to hay analysis.

In the second decade of this century, Pfeiffer and his collaborators at Breslau returned to the attack on the problem of the diagnosis of the nutrient needs of cereals. At first their interest in the problem was casual ; in the course of a paper on the effect of water, light and nitrogen supply on the growth and composition of oat grain and straw (Pfeiffer *et al.*, 1912), it was pointed out that the results had a bearing on the choice of an organ for analysis where the determination of fertilizer requirements was in question. " In the determination of limiting values at which nitrogen fertilizer applications begin to be unremunerative, the straw should perhaps be taken primarily into account." The attempts made by several workers (Wolff, 1876, 1877 ; Heinrich, 1882 ; Atterberg, 1901) to specify minimal percentages, an approach to which indicated deficiency, was criticised ; to the Breslau workers it seemed that, on the contrary, " Maximal values at which further nutrient supply causes no increase in yield, at which luxury consumption in the true sense commences, must be determined, so that in any particular case it can be found how far the observed values fall below the maximum."

Subsequently (Pfeiffer *et al.*, 1915) an experiment was set up deliberately to test the possibilities of plant analysis for estimating soil nutrient supplies. The experiment was carried out in pots, since it was thought that control of water supply was important ; oats was the test plant, and seven different soils were used. To some pots incomplete fertilizers lacking one of the three principal nutrients were applied, while others were left untreated. The plants were harvested at the milk-ripe stage and they were analysed for nitrogen, phosphorus and potassium. The point of view adopted was that the percentage of an element in the material from pots receiving fertilizer without this element would represent a minimal value (" *Normalgehaltszahl* ") ; and the extent to which the corresponding percentage in the control pot exceeded this minimal value would indicate the available supply of the nutrient in the soil in question. Though it was found in fact that the " minimal values " for nitrogen and phosphorus fell within a fairly narrow range, those for potassium varied greatly ; evidently some of the soils were so well supplied with potassium that even under conditions of maximum yield luxury consumption was taking place. Since the uptake of potassium and phosphorus was increased by the application of fertilizers not containing these elements, it was not considered that analysis of plants from the control pots would give useful information on the availability of these elements. The relationships found with nitrogen were more satisfactory, and the mean " minimal value " found (0.759%) agreed passably well with that found by Liebscher *et al.* (1898) (0.649%). The suggestion was repeated that, in addition to the " minimal values " it might be desirable to establish " maximal values " for mineral content above which no yield increases should be expected.

Later, the Breslau workers (Pfeiffer *et al.*, 1919) performed a series of experiments in sand culture in which oat plants were supplied with eleven different levels of the three principal nutrients under different conditions of watering and illumination. The plants were harvested at the milk-ripe stage and analysed for the elements whose supply had been varied. Yield curves of the Mitscherlich type were deduced without assuming the constancy of the effect factor. The relation of the yield to the nutrient content of the dry matter was then studied. For one of the nitrogen series, a hyperbolic function was found to fit these data fairly closely. Since, however, it was desirable to find a way of eliminating the effect of the different shading and watering conditions, the assumption was made that " for those points on the yield curve where the gradient divided by the yield gives the same values, the yields in question correspond to the same percentage nutrient content." On this basis curves were drawn by trial and error, and were found to represent tolerably well the relationship between yield on the one hand and content of nitrogen and phosphorus on the other. The curves for potassium agreed poorly with the observed points. It was suggested that, from the yield and nutrient content of plants grown on a given soil, it would be possible to deduce the Mitscherlich curve on which they lay, and hence to deduce the probable response to any proposed fertilizer application. It was pointed out, however, that the nutrient content of plants grown in soil is generally higher with a given yield than in sand cultures ; the yield responses to fertilizer treatment in the field would also differ from those in sand culture. Hence it would be premature to attempt to apply the results of these experiments to conditions in the field. Shortly after the publication of this paper, Mitscherlich (1919) tested the assumption that a given nutrient content of the plant material always corresponded to the same slope of the yield curve, but found it did not apply to the data he used, which involved a comparison of three phosphatic fertilizer materials. Lange (1926), too, came to the conclusion that his results with oats grown in pot culture on different soils did not bear out Pfeiffer's hypothesis.

Münter (1919, 1920) used data from a long-term rotational manurial trial to test the possibilities of plant analysis as a means of assessing fertilizer requirements. The material used was drawn from five consecutive years and eight manurial treatments, and the crops for which data were given were wheat and sugar beet. The only materials in which Münter considered that the percentage nutrient content could give a direct indication of the fertilizer requirements of the soil were the tops and roots of sugar beet, which could shew the phosphorus status (see limiting values, Table XII). For the other nutrients and for the wheat grain and straw the effects on composition of varying weather in the different years were held to be too great to make the use of these data possible.

For the nitrogen status Münter thought that the total uptake per unit area of ground pro-

vided a better index, and suggestions were also made of limiting values for certain ratios of the nutrients in the plant material (Table XV). He considered that the fertilizer requirements of a field could be best diagnosed by analysis of material from small plots treated, on the one hand, with nitrogenous fertilizer only, and on the other with a fertilizer containing potassium and phosphorus but no nitrogen.

The work described in the preceding pages has been discussed in some detail, not necessarily because it is intrinsically important, but because it has been almost forgotten. In reading much of the recent literature on the subject one receives the impression that the diagnostic use of plant analysis began in the nineteen-twenties, and reference is hardly ever made to the earlier work. However, although some of this earlier work rested on a rather inadequate experimental foundation and none of the investigators could make use of modern techniques of statistical analysis, some of the experiments they described will stand comparison with most recent work on the subject, and present-day experimenters can certainly learn from a perusal of their papers.

That work prior to 1920 has largely been forgotten is doubtless partly due to the great expansion since that date ; but it must also be remembered that most of the earlier work was performed in German-speaking countries, and that in later years the interests of agricultural chemists in those countries have been concentrated upon the development of biological methods of soil analysis—particularly those of Mitscherlich and Neubauer. The great majority of investigations during more recent years on the diagnostic use of plant analysis have been carried out in English-speaking countries ; the language barrier has probably increased the neglect of earlier work published in German.

## RECENT WORK ON DIAGNOSTIC PLANT ANALYSIS

The reasons for the great expansion during the past twenty-five years in work on plant analysis for diagnostic purposes, which is in part the cause of the oblivion into which earlier work has fallen, are diverse. One is unquestionably the increasingly recognized importance of deficiencies of the trace elements. Another appears to be the increasing attention paid by agricultural chemists and agricultural research workers in general to the horticultural crops—in which deficiencies can not only more often be recognized during growth than in the field crops, but also more easily be remedied. A third contributory reason is doubtless the improvements which have been introduced into analytical technique—particularly those which have facilitated the rapid analysis of large numbers of samples, such as the development of colorimetric and spectrographic methods. Finally, the virtual abandonment by most investigators of the conception of plant analysis as a biological method of soil analysis, and its replacement by an interest in the nutritional condition of the plant itself irrespective of its relation to nutrient supplies in the soil played a part in the later development of these methods ; as has already been shewn, many of the earlier workers were interested primarily in soil conditions, though von Dikow (1891) and Atterberg (1901) realized that plant analyses could be expected to give information mainly on the nutrient needs of the plants, and not of the soils.

Developments during the past quarter of a century in the diagnostic use of plant analysis can be discussed in the present section only in fairly general terms. Most of the investigations can be included in one of the groups below :—

(1) Investigation of nutritional disorders made manifest by definite symptoms.
(2) Interpretation of the results of field trials.
(3) Development of rapid testing methods for use in advisory work.
(4) Use of plant analysis as a method of nutritional survey.

These categories are, of course, far from mutually exclusive, but they will serve as convenient pegs on which to hang the following paragraphs.

### Identification of Symptoms of Nutritional Disorders

We will first consider those investigations in which plant analysis has contributed to the recognition of symptoms of nutritional disorders. Such investigations have been carried out

at a great many institutions in all parts of the world, and the general course of events has been: (a) the disorder is distinguished from others and a clinical picture of the symptoms obtained; (b) attempts are made to identify its cause by soil analysis, analysis of affected plants, or tentative treatment with elements which it is thought may be deficient, or by trying to reproduce the symptoms in sand or solution culture; generally a combination of several of these methods has been used, and often the presence locally of deficiency diseases of other crop plants has provided important clues; (c) when these attempts have met with success, and (in most cases) have led to a satisfactory means of control, the symptoms alone can generally be used as a method of identification in particular cases, and only where the symptoms are doubtful, or (often) where the disorder is observed for the first time in a new region, is it necessary to confirm the diagnosis by some other technique—a role which plant analysis can often play.

In some instances the order of the first two stages has been reversed—symptoms of a disorder have first been induced in sand or solution culture, and have later been recognized in the field; but in such cases confirmation of the identification of the field symptoms is usually necessary.

Among the many nutritional disorders in which analysis of the affected plants provided the first clue to their etiology may be mentioned potassium deficiency of plum (Wallace, 1928b), grape-vine (Herschler, 1933), rhubarb (Carolus, 1936, 1938; Carolus *et al.*, 1938), tung (Drosdoff and Painter, 1942; Drosdoff, 1943), and peach (Dunbar and Anthony, 1943); calcium deficiency of the potato (Roach, 1945); magnesium deficiency of orange (Parbery, 1935), grapefruit (Fudge, 1938, 1939), pine (Becker, 1940), pineapple (Quiñones, 1940), tomato (Cromwell and Hunter, 1942) and tung (Drosdoff and Kenworthy, 1944); boron deficiency in orange (Morris, 1937); manganese deficiency in bracken (Hunter, 1942) and cherry (Duggan, 1943; Roach, 1944); copper deficiency in plum (Anderssen, 1932), grape-vine (Teakle *et al.*, 1943) and tung (Drosdoff and Dickey, 1943); chlorine toxicity in avocado (Haas, 1929, 1936); manganese toxicity in French bean (Parbery, 1941, 1943); and combined potassium, manganese and iron deficiency in deciduous fruit trees (Roberts, 1945). Instances in which analysis of plant material has provided confirmation of a tentative diagnosis based on other grounds are, of course, even more numerous.

Occasionally plant analysis has been used to correct an unjustified identification of symptoms. For instance, " frenching " of tobacco had been considered identical with the symptoms induced by thallium toxicity until it was shewn that no thallium could be found in " frenched " plants by spectrographic analysis, although it could readily be demonstrated in plants with even slight toxicity symptoms (Spencer and Lavin, 1939; Shear and Ussery, 1940). A chlorosis of peanut plants was thought to be nutritional until their composition was found to be normal, when it was identified as due to leaf-hopper injury (Burkhart, 1941). Analysis of the plant material has enabled spray injury to be distinguished from potassium deficiency in the apple (Gardiner, 1940) and cases of corky split veins due to boron deficiency and to other causes to be distinguished in citrus (Haas, 1945).

In view of the value of plant analysis in providing confirmation of an uncertain diagnosis by deficiency symptoms, a table has been prepared (Table I) in which many of the published data on the content of nutrients in plants shewing symptoms of nutritional disorders have been reproduced in summary form and contrasted with data for otherwise comparable plants not shewing the symptoms. The investigations from which these data are derived vary greatly in value; it is hardly possible to indicate this in the table—even the number of samples included has been omitted—but the information in column 5 shews one respect in which data from different sources are not fully comparable, giving the size of the unit from which each sample was taken and to which the statement as to the presence or absence of symptoms applies. If one assumes a limiting value for the content of a nutrient above which no symptoms appear, but that the content continues to increase above this level with increasing supply, it is clear that a sample for analysis taken at random on a plot where only some plants shew symptoms will not represent those plants properly, and may even shew a higher content of the deficient nutrient than a sample from another plot without symptoms. It has not been possible in the table to distinguish between different intensities of symptoms, so (except in cases indicated by the footnote (Q)) the figures in columns 7 and 9 represent the extreme range for all samples drawn from material shewing

symptoms, no matter how slight, while those in column 8 give the extreme range for samples from areas, plants or organs showing no symptoms whatever. Varietal differences have not in general been indicated, and the ranges of composition shewn often include data from several varieties; most investigators agree, however, that varietal differences in nutrient content are usually relatively small (see pp. 113-114).

The symptoms included in Table I are all recognizable abnormalities, and not merely delays or reduction in flowering, reduced or spindly growth, or paler leaf colour.

It will be noted that Tables I and II contain no reference to iron deficiency. The reason for this is that the relation between iron deficiency and the iron content of the plant is still very far from clear. Many chloroses can be cured by a superficial application of a solution of ferrous sulphate to the leaves in the form of a paint or spray, or by injection of iron compounds; and yet the chlorotic plants are often found to contain no less—or even more—iron than normal ones (Gile, 1911; Averna-Saccá, 1912; Milad, 1925, 1939; Oserkowsky, 1932, 1933; Wann, 1934; Olsen, 1935; Iljin, 1943; Lindner and Harley, 1944; Roach, 1944). Admittedly, a number of other cases have been reported where the iron content of the chlorotic leaves is subnormal (Wallace and Mann, 1926; Wallace, 1928; Loehwing, 1928; Ravaz *et al.*, 1928; Chapman, 1931; Scholz, 1933; Milad, 1939; Guest, 1943; Thorne and Wallace, 1944; Bennett, 1945); but the relationship does not appear to be at all regular or trustworthy, though occasionally (Guest, 1941) analysis has given useful diagnostic indications. According to Jacobson (1945), surface contamination may be responsible for much of the disagreement between iron deficiency symptoms and iron content of leaves. The suggestion has been made (Oserkowsky, 1933) that only a certain fraction of the iron present in the plant is "active"; Oserkowsky himself identified this "active" iron with that soluble in N hydrochloric acid, but Lindner and Harley (1944) found that in lime-induced chlorosis the fraction soluble in 0.5 N hydrochloric acid but not in 0.1 N hydrochloric acid was most consistently related to the symptoms, though this did not apply to other types of chlorosis curable by iron. It appears that for the present reliance must be placed on methods other than plant analysis for the diagnosis of iron deficiency.

## Table I.

**Content of nutrients in plant material in relation to the incidence of deficiency or toxicity symptoms.**

*N.B.—Letters in columns 3—5 and 7—9 refer to Notes at end of Table.*

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of element in dry matter, unless otherwise indicated. Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| APPLE (*Pyrus malus*, etc.) | | | | | | | | | |
| | K | A | ———— | J | Leaves | 0.23-0.35 | 0.41-1.61 (Q) | | Wallace 1931 |
| | K | D | Oct. | J | Leaves | 0.33-0.68 | 0.83-2.31 | | Batjer & Degman 1940 |
| | K | A | July-Aug. | J | Leaves | 0.28-0.90 | 0.56-1.49 | | Reuther & Boynton 1940 |
| | K | A | Sept. | J | Leaves | 0.25-0.46 | 0.49-0.66 | | Burrell & Cain 1941 |
| | K | D (?) | ———— | I | Leaves | 0.37-0.59 | 1.70-2.90 | | Edgerton 1941 |
| | K | $A,B_I$ | July-Aug. | J | Leaves from middle of terminal shoots | 0.28-0.95 | 0.40-1.56 (Q) | | Reuther 1941a |
| | K | $B_I$ | Late July | I | Shoot leaves | 0.56-0.58 | 1.16-2.18 | | Burrell & Boynton 1943 |
| | K | $B_I$, D | June-Sept. | I, K | Leaves | 0.6-0.75 | 1.01-3.0 | | Boynton & Burrell 1944a |
| | K | A | July-Oct. | J | Leaves | 0.45-0.93 | 1.53-2.04 | | Goodall 1945 |
| | K | $B_I$ | July-Sept. | I | Leaves | 0.57-1.01 | 0.73-1.86 | | Nicholas & Jones 1945 |
| | K | D | Nov. | J | Bark | 0.639-0.740 | 0.682-1.049 | | Batjer & Degman 1940 |
| | Mg | D | June-July | J | Leaves | 0.0628-0.0937 | 0.1179-0.4140 | | Wallace 1929 |
| | Mg | A | Feb.-Mar. (F) | G | Leader tip leaves | 0.17-0.38 | 0.32-0.78 | | Kidson *et al.* 1940 |
| | Mg | A | Feb.-Mar. (F) | G | Older leader leaves | 0.052-0.17 | 0.22-0.45 | | Kidson *et al.* 1940 |
| | Mg | A | ———— | G | Leaves | 0.72-1.51 (N) | 3.0-4.2 (N) | | Hill & Johnston 1940 |
| | Mg | A, $B_I$ | July-Sept. | G, I | Leaves near base of terminal shoots | 0.05-0.19 | 0.18-0.29 | | Wallace 1940 |
| | Mg | $B_I$ | July | I | Older leaves of current season's shoots | 0.13-0.18 | 0.14-0.19 | | Wallace 1940a |
| | Mg | A, $B_I$ | ———— | — | Leaves | 1.3-3.3 (N) | 3.6-4.9 (N) | | Hill 1941 |
| | Mg | $B_2$ | July | L | Median shoot leaves | 0.02-0.33 | 0.21-0.53 | | Boynton *et al.* 1943 |
| | Mg | $B_I$ | Midsummer | I | Median shoot leaves | 0.07-0.19 | 0.11-0.21 (Q) | | Boynton *et al.* 1943 |
| | Mg | C | July | I | Leaves | 0.23-0.47 | 0.64-1.13 | | Southwick 1943 |
| | Mg | A | Aug. | J | Median shoot leaves | 0.09-0.23 | 0.23-0.35 | | Southwick 1943 |
| | Mg | $B_I$, D | June-Sept. | I, K | Leaves | 0.08-0.20 | 0.16-0.72 | | Boynton & Burrell 1944a |
| | Mg | A | July-Oct. | J | Leaves | 0.138-0.184 | 0.191-0.289 | | Goodall 1945 |
| | Mg | $B_I$ | July-Sept. | I | Leaves | 0.05-0.23 | 0.20-0.25 | | Nicholas & Jones 1945 |
| | Mg | $B_I$ | July | I | Median shoot leaves | 0.08-0.20 | 0.11-0.27 | | Boynton 1945a |
| | Mg | A, $B_I$ | Early summer | I | Petioles (2% acetic acid extract) | 0.0125-0.0250 (O) | 0.0500-0.0750 (O) | | Hill & Johnston 1940 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mg | D | Dec.-Jan. | J | Shoot bark | 0.088 | 0.163-0.293 | | Wallace 1929 |
| Mg | D | Dec.-Jan. | J | Shoot wood | 0.042 | 0.0743-0.0834 | | Wallace 1929 |
| Mg | D | Dec. | J | Trunk bark | 0.0651-0.0669 | 0.1620-0.1860 | | Wallace 1929 |
| Mg | D | Dec. | J | Trunk wood | 0.0126-0.0168 | 0.0316-0.0446 | | Wallace 1929 |
| Mg | D | June-July | J | Stems and petioles | 0.118-0.159 | 0.192-0.330 | | Wallace 1929 |
| Mg | A, $B_1$ | Early summer | I | Terminal shoots (2% acetic acid extract) | 0.0750 (O) | 0.1000-0.1500 (O) | | Hill & Johnston 1940 |
| B | A | ———— | K | Leaves | 0.0009-0.0011 | 0.0017-0.0018 | | Askew, 1935 |
| B | A, $B_2$ | ———— | K | Leaves | 0.00151-0.00204 | 0.00250-0.00346 | | Askew & Chittenden 1936 |
| B | $B_1$ | Feb. (F) | I | Leaves | 0.00126-0.00257 | 0.00213-0.00281 (Q) | | Askew *et al.* 1936 |
| B | A | ———— | K | Leaves | 0.000481-0.000683 | 0.001080-0.001826 | | McLarty *et al.* 1936 |
| B | $B_1$ | ———— | K | Leaves | 0.00102-0.00150 | 0.00133-0.00280 | | Woodbridge 1937 |
| B | A | ———— | G | Leaves | 0.00048-0.00161 | 0.00108-0.00247 | | Woodbridge 1937 |
| B | A | ———— | K | Twigs | 0.000649-0.000930 | 0.001135-0.001417 | | McLarty *et al.* 1936 |
| B | $B_1$ | ———— | K | Twigs | 0.00060-0.00120 | 0.00087-0.00218 | | Woodbridge 1937 |
| B | A | ———— | K | Twigs | 0.000489-0.001362 | 0.001122-0.001525 | | Woodbridge 1937 |
| B | A | ———— | G | Twigs | 0.00059-0.00115 | 0.00087-0.00150 | | Woodbridge 1937 |
| B | A | ———— | K | Fruit | 0.0003-0.0008 | 0.0010-0.0013 | | Askew 1935 |
| B | A, $B_2$ | ———— | K | Fruit | 0.00036-0.00084 | 0.00175-0.00761 | | Askew & Chittenden 1936 |
| B | A | ———— | K | Fruit | 0.000226-0.000454 | 0.000967-0.002762 | | McLarty *et al.* 1936 |
| B | $B_1$ | Mar. (F) | I | Fruit flesh | 0.00039-0.00112 | 0.00100-0.00306(Q) | | Askew *et al.* 1936 |
| B | $B_3$ | Mar. (F) | L | Fruit | 0.00036-0.00079 | 0.00084-0.00404 | | Askew & Chittenden 1936a |
| B | $B_1$ | ———— | G | Fruit | 0.00046-0.00078 | 0.00122-0.00341 | | Askew & Thomson 1937 |
| B | A | ———— | G | Fruit | 0.00021-0.00065 | 0.00050-0.00276 | | Woodbridge 1937 |
| B | A | ———— | G | Fruit | 0.00039-0.00089 | 0.0016-0.0020 | | Chittenden & Thomson 1938 |
| B | A | ———— | G | Fruit without seeds | 0.00040-0.00097 | 0.00090-0.00341 | | Askew & Thomson, 1939 |
| B | $B_1$ (?) | ———— | K, $K_1$ | Fruit | 0.000248 | 0.000462-0.000543 | | Heinicke *et al.* 1942 |
| Mn | A | ———— | J | Basal leaves on current growth | 0.0005 | 0.00549-0.01246 | | Epstein & Lilleland 1942 |
| Cu | A, $B_1$ $B_2$ | ———— | K | Uppermost 4 leaves | 0.0001-0.0004 | 0.00032-0.0012 | | Dunne 1938 |
| Zn | A, B | Sept.-Oct. | K | Leaves (of apical 6"-8") | 0.0004-0.0054 | 0.0004-0.0080 | | Chandler *et al.* 1934 |
| Zn | A, B | Sept.-Oct. | K | Stems (apical 6"—8") | 0.0004-0.0028 | 0.0016-0.0080 | | Chandler *et al.* 1934 |
| APRICOT (*Prunus armeniaca*) | | | | | | | | |
| B | A | Oct. | J | Leaves | ———— | 0.0052 | 0.0082 | Eaton, F. M., 1935 |
| B | $B_1$, $B_3$ | Dec. (F) | I | Leaves | 0.00125 | 0.00320-0.00405 (Q) | ———— | Askew & Williams 1939 |
| B | D | June | K | Leaves | 0.00025-0.00068 | 0.00216-0.00295 (Q) | ———— | Fitzpatrick & Woodbridge 1941 |
| B | A | ———— | K | Leaves | ———— | 0.0049 | 0.0118 | Eaton *et al.* 1941 |
| B | A | Oct. | J | Twig bark | ———— | 0.0038 | 0.206 | Eaton, F. M., 1935 |
| B | A | Oct. | J | Twig wood | ———— | 0.0023 | 0.0082 | Eaton, F. M., 1935 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of elements in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| APRICOT (*Prunus armeniaca*)—continued | | | | | | | | | |
| | B | A | ———— | K | Twig bark | ———— | 0.0022 | 0.0063 | Eaton *et al.* 1941 |
| | B | A | ———— | K | Twig wood | ———— | 0.0005 | 0.0027 | Eaton *et al.* 1941 |
| | B | A | Spring | K | Twigs | 0.00045 | 0.00200-0.00208 | ———— | Fitzpatrick & Woodbridge 1941 |
| | B | $B_1$, $B_3$ | Dec. (F) | I | Fruit | 0.00057 | 0.00345-0.00465 (Q) | ———— | Askew & Williams 1939 |
| | B | A | ———— | K | Fruit flesh | ———— | 0.0041 | 0.0441 | Eaton *et al.* 1941 |
| | B | A | ———— | K | Fruit shell | ———— | 0.0003 | 0.0052 | Eaton *et al.* 1941 |
| | B | A | ———— | K | Seeds | ———— | Trace | 0.0085 | Eaton *et al.* 1941 |
| | Zn | A, B | Sept. Oct. | K | Leaves (of apical 6"—8") | 0.0024-0.0030 | 0.0019-0.0031 | ———— | Chandler *et al.* 1934 |
| | Zn | A, B | Sept.-Oct. | K | Stems (apical 6"—8") | 0.0007-0.0009 | 0.0011-0.0034 | ———— | Chandler *et al.* 1934 |
| ARTICHOKE (*Cynara scolymus*) | | | | | | | | | |
| | B | D | Mar. | I | Leaf laminae | 0.0038 | 0.0112 | 0.0236-0.1358 | Eaton 1944 |
| | B | D | Mar. | I | Plant | 0.0028 | 0.0087 | 0.0155-0.0817 | Eaton 1944 |
| ASPARAGUS (*A. officinalis*) | | | | | | | | | |
| | B | D | May-Oct. | I | Tops | 0.0043-0.0055 | 0.0054-0.0244 | 0.0175-0.0288 | Eaton 1944 |
| | B | D | May | I | Roots | 0.0013 | 0.0016-0.0030 | 0.0059 | Eaton 1944 |
| AVOCADO (*Persea americana*) | | | | | | | | | |
| | B | E | ———— | K | Leaves | 0.000276-0.000818 (M) | 0.001133-0.003757 (M) | ———— | Haas 1943 |
| | B | E | ———— | K | Leaves | 0.000626-0.001200 ($M_I$) | 0.000975-0.002000 ($M_I$) | ———— | Haas 1943 |
| | Cl | A | Jan.-May | G | Leaves | ———— | 0.09-0.032. | 0.54-1.34 | Haas 1929 |
| | Cl | A | ———— | G | Fruit pulp (stem half) | ———— | 0.014-0.090 | 0.102-0.301 | Haas 1936a |
| | Cl | A | ———— | G | Fruit pulp (tip half) | ———— | 0.013-0.060 | 0.097-0.267 | Haas 1936a |
| | Cl | A | ———— | G | Fruit skin (stem half) | ———— | 0.022-0.190 | 0.127-1.280 | Haas 1936a |
| | Cl | A | ———— | G | Fruit skin (tip half) | ———— | 0.024-0.110 | 0.096-1.000 | Haas 1936a |
| BARLEY (*Hordeum vulgare*) [*see also* Cereals] | | | | | | | | | |
| | B | D | July | I | Grain | ———— | 0.0003-0.0011 | 0.0012-0.0051 | Eaton 1944 |
| | B | D | July | I | Plant | ———— | 0.0015-0.0078 | 0.0219-0.1111 | Eaton 1944 |
| BEET (*Beta vulgaris*) [*see also* Chard, Mangold, Sugar Beet.] | | | | | | | | | |
| | B | D | Aug. | I | Leaf laminae | 0.0052 | 0.0104-0.0370 | 0.0637-0.1263 | Eaton 1944 |
| | B | A, $B_I$ | ———— | J | Roots | 0.00111-0.00123 | 0.00115-0.00137 | ———— | Brandenburg 1932 |
| | B | A, $B_I$ | ———— | J | Roots | 0.0184-0.0503 (N) | 0.0603-0.0771 (N) | ———— | Brandenburg 1932 |
| | B | D | Aug. | I | Roots | 0.0033 | 0.0016-0.0046 | 0.0044-0.0082 | Eaton 1944 |
| | B | D | Aug. | I | Plant | 0.0038 | 0.0043-0.0138 | 0.0198-0.0386 | Eaton 1944 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **BLACK CURRANT** (*Ribes nigrum*) | | | | | | | | |
| K | $B_I$ | Sept. | I | Leaves | 0.78 | 0.91-1.06 | ——— | Wallace & Osmond 1941 |
| Mg | $B_I$ | July | I | Leaves | 0.11-0.43 | 0.26-0.45 | ——— | Wallace 1940a |
| **BRUSSELS SPROUT** (*Brassica oleracea* var.) | | | | | | | | |
| B | $B_I$, D | Oct. | I | Leaves | 0.0005-0.0014 | 0.0023-0.0049 (Q) | ——— | Maier 1944 |
| **CABBAGE** (*Brassica oleracea*) | | | | | | | | |
| N | A | ——— | J | Petioles (2% acetic acid extract) | 0.0078 (O) | 0.0518 (O) | ——— | Carolus 1938; Carolus *et al.* 1938 |
| Mg | A | ——— | J | Leaf bases | 0.092 | 0.165-0.178 | ——— | Carolus 1935 |
| Mg | A | ——— | J | Leaf tips | 0.037 | 0.076-0.119 | ——— | Carolus 1935 |
| Mg | A | ——— | G | Upper leaves (2% acetic acid extract) | 0.0015-0.0018 (O) | 0.0060 (O) | ——— | Carolus 1936 |
| Mg | A | ——— | G | Lower leaves (2% acetic acid extract) | 0.0012 (O) | 0.0045-0.0068 (O) | ——— | Carolus 1936 |
| Mg | A | ——— | G | Stems (2% acetic acid extract) | 0.0036 (O) | 0.0060-0.01666 (O) | ——— | Carolus 1936 |
| Mg | A, $B_I$ | Seedling stage | G, I | Tops | 0.43 | 0.56-0.57 | ——— | Parbery 1937 |
| B | $B_I$, D | Nov. | I | Leaves | 0.0005-0.0018 | 0.0022-0.0038 | ——— | Maier 1944 |
| B | D | Apr. | I | Outer leaves | ——— | 0.0016-0.0204 | 0.0440-0.1152 | Eaton 1944 |
| B | D | Apr. | I | Inner leaves | ——— | 0.0022-0.0055 | 0.0060-0.0110 | Eaton 1944 |
| B | D | Apr. | I | Plant | ——— | 0.0021-0.0081 | 0.0263-0.0713 | Eaton 1944 |
| **CACAO** (*Theobroma cacao*) | | | | | | | | |
| K | D | ——— | J | Leaf laminae | 1.85 | 2.81-3.27 | ——— | Hardy 1937 |
| K | A, $B_1$ | ——— | J | Leaf laminae | 0.55-1.94 | 1.43-1.68 (Q) | ——— | Hardy 1937 |
| **CALENDULA** (*C. officinalis*) | | | | | | | | |
| B | D | Apr. | I | Leaves | ——— | 0.0053-0.0272 | 0.0715-0.2106 | Eaton 1944 |
| B | D | Apr. | I | Plant | ——— | 0.0019-0.0121 | 0.0324-0.1025 | Eaton 1944 |
| **CARPET GRASS** (*Axonopus affinis*) | | | | | | | | |
| P | $B_I$ | Summer | I | Clippings | 0.100-0.107 | 0.157-0.234 | ——— | Blaser & Stokes 1943 |
| K | $B_I$ | Summer | I | Clippings | 0.401 | 0.366-0.934 | ——— | Blaser & Stokes 1943 |
| **CARROT** (*Daucus carota*) | | | | | | | | |
| N | D | ——— | I | Petioles (2% acetic acid extract) | 0.0055 (O) | 0.0521-0.0833 (O) | ——— | Hill 1943 |
| P | D | ——— | I | Petioles (2% acetic acid extract) | 0.0015-0.0022 (O) | 0.0125-0.0250 (O) | ——— | Hill 1943 |
| K | D | ——— | I | Petioles (2% acetic acid extract) | 0.054 (O) | 0.328-0.647 (O) | ——— | Hill 1943 |
| B | D | Apr.-Sept. | I | Leaf laminae | ——— | 0.0036-0.0204 | 0.0324-0.1244 | Eaton 1944 |
| B | D | Apr.-Sept. | I | Roots | ——— | 0.0022-0.0064 | 0.0065-0.0319 | Eaton 1944 |
| B | D | Apr.-Sept. | I | Plant | ——— | 0.0027-0.0116 | 0.0189-0.0570 | Eaton 1944 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of element in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| CELERY (*Apium graveolens*) | | | | | | | | | |
| | B | A, $B_I$ | Oct. | J | Leaves | 0.0015 | 0.0027-0.0048 | ——— | Maier 1943 |
| | B | D | Mar. | I | Leaflets | 0.0020 | 0.0068-0.0432 | 0.0720 | Eaton 1944 |
| | B | A, $B_I$ | Oct. | J | Crowns | 0.0013 | 0.0019-0.0029 | ——— | Maier 1943 |
| | B | A, $B_I$ | Oct. | J | Roots | 0.0022 | 0.0027-0.0040 | ——— | Maier 1943 |
| | B | D | Mar. | I | Plant | 0.0026 | 0.0063-0.0400 | 0.0729 | Eaton 1944 |
| CEREALS [*see also* Barley, Maize, Milo, Oats, Rice, Rye, Wheat] | | | | | | | | | |
| | Mg. | ? | Young | ? | Plant | 0.15-0.51 | 0.24-0.58 | ——— | van Itallie 1937 |
| CHARD (*Beta vulgaris* var. *cicla*) [*see also* Beet] | | | | | | | | | |
| | B | D | Mar. | I | Plant | ——— | 0.0016-0.0139 | 0.0200 | Eaton 1944 |
| CHERRY (*Prunus cerasus* etc.) | | | | | | | | | |
| | K | $B_I$ | July | I | Leaves | 0.39-1.82 | 2.06-2.13 | ——— | Boynton 1944 |
| | B | D | Nov. | I | Leaves | 0.0014 | 0.0104 | 0.0182 | Eaton 1944 |
| | B | D | Nov. | I | Stems | 0.0002 | 0.0023 | 0.0085 | Eaton 1944 |
| | B | D | Nov. | I | Roots | 0.0002 | 0.0054 | ——— | Eaton 1944 |
| | Mn | A | ——— | J | Basal leaves on current growth | 0.0021 | 0.00539-0.00717 | ——— | Epstein & Lilleland 1941 |
| CITRUS [*see also* Grape-fruit, Lemon, Orange] | | | | | | | | | |
| | Mg | A | Autumn | L | Leaves | 0.0251-0.0469 | 0.103-0.184 | ——— | Bahrt & Hughes 1937 |
| | B | A, $B_I$ | ——— | K | Leaves | ——— | 0.0031-0.0177 | 0.0325-0.1162 | Scofield & Wilcox 1931 |
| | Mn | A | ——— | K (?) | Leaves | 0.00037-0.00049 | 0.0014-0.0020 | ——— | Chapman *et al.* 1939 |
| | Zn | A | ——— | L | Leaves | 0.00038-0.00117 | 0.00078-0.00160 | ——— | Gaddum *et al.* 1937 |
| | Zn | A | ——— | L | Twigs & petioles | 0.00051-0.00093 | 0.00054-0.00271 | ——— | Gaddum *et al.* 1937 |
| | Zn | — | ——— | — | Young leaves | 0.0005-0.0020 | usually >0.0020 | ——— | Grimmett 1938 |
| | Na | D | ——— | K | Older leaves | ——— | 0.026 | 0.88 | Chapman & Brown 1943 |
| COTTON (*Gossypium hirsutum*) | | | | | | | | | |
| | B | D | Nov. | I | Leaves | 0.0016 | 0.0187-0.0306 | 0.0522-0.1625 | Eaton 1932, 1944 |
| | B | D | Nov. | I | Stems and roots | 0.0015 | 0.0024-0.0032 | 0.0033-0.0060 | Eaton 1932, 1944 |
| COWPEA (*Vigna sinensis*) | | | | | | | | | |
| | K | A | ——— | J | Stems and petioles (?) (2% acetic acid extract) | 0.0041 (O) | 0.4980 (O) | ——— | Carolus 1936 |
| | B | D | Aug. | I | Leaves | ——— | 0.0032-0.0119 | 0.0404-0.1132 | Eaton 1944 |
| | B | D | Aug. | I | Plant | ——— | 0.0027-0.0070 | 0.0195-0.0573 | Eaton 1944 |
| FIELD BEAN (*Vicia faba*) | | | | | | | | | |
| | K | A | May-June | J | Upper leaves | 0.58-1.19 | 1.05-1.75 | ——— | Large 1945a |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| FIG (*Ficus carica*) | | | | | | | | |
| B | D | Nov. | I | Leaves | 0.0015 | 0.0404 | 0.0722-0.1296 | Eaton 1944 |
| B | D | Nov. | I | Roots | 0.0010 | 0.0028 | 0.0063 | Eaton 1944 |
| FLAX (*Linum usitatissimum*) | | | | | | | | |
| Ca | A | ——— | J | Tops | 0.20-0.45 | 0.37-0.52 | ——— | Millikan 1944 |
| FRENCH BEAN = KIDNEY BEAN (*Phaseolus vulgaris*) | | | | | | | | |
| B | D | Aug. | I | Leaves | ——— | Trace | 0.0151-0.1733 | Eaton 1944 |
| B | D | Aug.-Sept. | I | Plant | ——— | 0.0006-0.0012 | 0.0085-0.0997 | Eaton 1944 |
| Mn | $B_1$ | ——— | I | Plant | ——— | 0.0032-0.0068 | 0.0207-0.1340 | Parbery 1943 |
| GOOSEBERRY (*Ribes grossularia*) | | | | | | | | |
| K | $B_1$ | June | I | Leaves of terminal shoots | 0.534-0.880 | 1.476-1.670 | ——— | Wallace 1928a |
| K | $B_1$ | July | I | Older leaves of current season's shoots | 0.80-0.91 | 1.93-4.24 | ——— | Wallace 1940a |
| K | $B_1$ | June | I | Stems of terminal shoots | 0.473-0.529 | 0.920-1.055 | ——— | Wallace 1928a |
| K | $B_1$ | June | I | Fruit | 0.965-1.202 | 1.170-1.734 | ——— | Wallace 1928a |
| Mg | $B_1$ | July | I | Older leaves of current season's shoots | 0.17-0.37 | 0.25-0.31 | ——— | Wallace 1940 |
| GRAPE (*Vitis* spp.) | | | | | | | | |
| K | $B_1$ | ——— | I | Leaf laminae | 0.27-0.59 | 0.45-0.78 | ——— | Askew 1944 |
| K | A | Sept. | K | Leaves | 0.25-0.27 | 0.56-0.61 (Q) | ——— | Boynton 1945b |
| K | $B_1$ | ——— | I | Fruit | 0.53-1.09 | 0.69-1.08 | ——— | Askew 1944 |
| B | $B_1$ | Aug. | K | Mature leaves | 0.0006-0.0024 | 0.0018-0.0054 | ——— | Scott 1941 |
| B | $B_1$ | ——— | I | Leaf laminae | 0.00055-0.00191 | 0.00291-0.00418 | ——— | Askew 1944 |
| B | D | Sept.-Nov. | I | Leaves | 0.0038-0.0086 | 0.0250-0.0267 | 0.0926-0.1804 | Eaton 1944 |
| B | D | Nov. | I | Stems | 0.0028 | 0.0050 | 0.0050-0.0155 | Eaton 1944 |
| B | $B_1$ | ——— | I | Fruit | 0.00044-0.00088 | 0.00150-0.00339 | ——— | Askew 1944 |
| Cu | A | Apr. (F) | K | Mature leaves | 0.00012-0.00018 | 0.00026-0.00039 | ——— | Teakle *et al.* 1943 |
| Cu | A | Dec. (F) | K | Leaves | 0.00021-0.00054 | 0.00075-0.00099 | ——— | Teakle *et al.* 1943 |
| Cl | A | ——— | K | Leaves | ——— | 0.04 | 1.07-3.84 | Ravikovitch & Bidner 1937 |
| Cl | A | ——— | K | Fruit | ——— | 0.09 | 0.29-1.50 | Ravikovitch & Bidner 1937 |
| GRAPEFRUIT (*Citrus paradisi*) [*see also* Citrus] | | | | | | | | |
| Mg | A | Oct. | J | Leaves | 0.122-0.228 | 0.013-0.017 | ——— | Fudge 1939 |
| B | A | ——— | K | Leaves | ——— | 0.0128-0.0468 (Q) | 0.0747-0.1522 | Scofield & Wilcox 1931 |
| B | $B_1$ | Sept. | I | Leaves of spring growth | ——— | 0.009-0.023 | 0.028-0.037 | Fudge 1943 |
| B | D | ——— | J | Leaves | 0.00050-0.00112 | 0.00330-0.01008 | ——— | Roy 1943 |
| Mn | A, $B_3$ | ——— | K | Leaves | 0.00088-0.00105 | 0.00347 | ——— | Levitt & Nicholson 1941 |
| Zn | $B_1$ | ——— | J | Leaves | 0.0004-0.0006 | 0.0008-0.0010 | ——— | McGeorge 1939 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of element in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| JERUSALEM ARTICHOKE (*Helianthus tuberosus*) | | | | | | | | | |
| | B | D | July | I | Dead leaves | ——— | 0.0171 | 0.0519-0.1590 | Eaton 1944 |
| | B | D | July | I | Plant | ——— | 0.0028 | 0.0098-0.1001 | Eaton 1944 |
| KIDNEY BEAN [*see* FRENCH BEAN] | | | | | | | | | |
| LEMON (*Citrus limonia*) [*see also* Citrus] | | | | | | | | | |
| | K | D | Oct. | I | Leaves | 0.05-0.39 | 1.55-2.62 | ——— | Chapman & Brown 1943 |
| | B | A, $B_1$ | ——— | J (?) | Leaves | 0.0266-0.1400 | 0.0019-0.0076 | ——— | Kelley & Brown 1928 |
| | B | A | ——— | K | Leaves | ——— | 0.0038-0.0380 (Q) | 0.0460-0.0922 | Scofield & Wilcox 1931 |
| | B | D | ——— | K | Leaves | 0.0020-0.0040 | 0.0152-0.0200 | ——— | Chapman and Brown 1943 |
| | B | D | Sept. | I | Leaves | ——— | 0.0061 | 0.0314-0.1232 | Eaton 1944 |
| | Mn | A, E | ——— | J | Leaves | 0.0002-0.0004 | 0.0014-0.0075 | ——— | Chapman *et al.* 1939 |
| LETTUCE (*Lactuca sativa*) | | | | | | | | | |
| | B | D | Aug. | I | Leaves | ——— | 0.0027-0.0043 | 0.0070-0.0817 | Eaton 1944 |
| | B | D | Aug. | I | Plant | ——— | 0.0025-0.0038 | 0.0058-0.0535 | Eaton 1944 |
| LUCERNE (*Medicago sativa*) | | | | | | | | | |
| | K | A | ——— | J | Leaves | 0.14 | 0.83 | ——— | Davies 1940 |
| | K | A | ——— | J | Stems | 0.9 | 0.8 | ——— | Davies 1940 |
| | B | A | ——— | G or H | Leaves | 0.000366-0.000950 | 0.00145-0.00322 | ——— | McLarty *et al.* 1937 |
| | B | $B_1$ | Late summer | I | Leaves | 0.0007-0.0014 | 0.0012-0.0038 | ——— | Dregne & Powers 1942 |
| | B | D | Apr.-Sept. | I | Leaves | ——— | 0.0028-0.0654 | 0.0516-0.0996 | Eaton 1944 |
| | B | D | Apr.-Sept. | I | Stems | ——— | 0.0011-0.0055 | 0.0028-0.0094 | Eaton 1944 |
| | B | D | Apr.-Sept. | I | Roots | ——— | 0.0020-0.0047 | 0.0052-0.0058 | Eaton 1944 |
| | B | D | Apr.-Sept. | I | Plant | ——— | 0.0016-0.0353 | 0.0247-0.0397 | Eaton 1944 |
| LUPIN (*Lupinus hartwegi*) | | | | | | | | | |
| | B | D | Apr. | I | Plant | ——— | 0.0027-0.0096 | 0.0367-0.0815 | Eaton 1944 |
| MAIZE (*Zea mays*) [*see also* Cereals] | | | | | | | | | |
| | K | $B_1$ | Aug. | I | Lower stems | 0.029-0.100 (P) | 0.334-0.595 (P) | ——— | Pettinger 1931 |
| | K | A | Early | H | Plant | 0.88-1.37 | 1.99-4.54 | ——— | Stanford *et al.* 1942 |
| | Ca | D | 25 days | I | Tops | 0.30 | 0.76-0.80 | ——— | Marsh & Shive 1941 |
| | Mg | $B_1$ | ——— | I | Leaf blades | 0.07 | 0.20 | ——— | Jones 1929 |
| | Mg | $B_1$ | ——— | I | Leaf sheaths | 0.07 | 0.24 | ——— | Jones 1929 |
| | Mg | $B_1$ | ——— | I | Stem nodes | 0.06 | 0.21 | ——— | Jones 1929 |
| | Mg | $B_1$ | ——— | I | Stem internodes | 0.04 | 0.10 | ——— | Jones 1929 |
| | B | D | Oct. | J | Leaves | ——— | 0.0027-0.0072 | 0.0179 | Eaton 1944 |
| | B | D | 25 days | I | Tops | 0.0001-0.0002 | 0.0005-0.0008 | 0.0025 | Marsh & Shive 1941 |
| | B | D | June | I | Plant | ——— | 0.0011-0.0032 | 0.0123-0.0727 | Eaton 1944 |
| | B | D | ——— | I | Plant | 0.0003-0.0019 (T) | 0.0019-0.0151 (T) | ——— | Reeve & Shive 1943 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MANGOLD (*Beta vulgaris* var.) [*see also* Beet] | | | | | | | | |
| B | A | ——— | J | Leaves | 0.0007-0.0021 | 0.0020-0.0049 | ——— | Brandenburg 1939 |
| B | A | ——— | J | Roots | 0.0016 | 0.0017 | ——— | Brandenburg 1939 |
| MILO (*Sorghum vulgare*) [*see also* Cereals] | | | | | | | | |
| B | D | Nov. | I | Leaves | ——— | 0.0016-0.0138 | 0.0625-0.2009 | Eaton 1944 |
| B | D | Nov. | I | Stalks & sheaths | ——— | 0.0011 | 0.0023-0.0261 | Eaton 1944 |
| B | D | Dec. | I | Plant | ——— | 0.0002 | 0.0007-0.0189 | Eaton 1944 |
| MUSKMELON (*Cucumis melo*) | | | | | | | | |
| B | D | Aug. | I | Leaves | ——— | 0.0037-0.0223 | 0.0923-0.3875 | Eaton 1944 |
| B | D | Aug. | I | Plant | ——— | 0.0028-0.0147 | 0.0530-0.2220 | Eaton 1944 |
| MUSTARD (*Brassica* sp.) | | | | | | | | |
| B | D | Jan. | I | Plant | ——— | 0.0049-0.0080 | 0.0108-0.0205 | Eaton 1944 |
| OATS (*Avena sativa*) [*see also* Cereals and Table XV]. | | | | | | | | |
| K | $B_1$ | Before maturity | I | Leaves | 0.295-0.444 | 1.150 | ——— | Lundegårdh 1932 |
| Ca | C | Flowering | K | Tops | 0.11-0.14 | 0.26 | ——— | Atterberg 1901 |
| Ca | D | Harvest | K | Straw | 0.10-0.14 | 0.36-0.64 | ——— | Atterberg 1901 |
| Mg | A, C | Apr.-May | I | Plant (?) | 0.10-0.39 | 0.18-0.52 | ——— | van Itallie 1936 |
| Mg | C | 4-6 leaf stage | I | Plant (?) | 0.073-0.255 | 0.127-0.286 | ——— | van Itallie 1937 |
| B | D | July | I | Grain | ——— | 0.0013-0.0019 | 0.0043-0.0419 | Eaton 1944 |
| B | D | July | I | Plant | ——— | 0.0006-0.0064 | 0.0283-0.1622 | Eaton 1944 |
| B | C | Starting to head | I | Plant | ——— | 0.0015-0.0050 | 0.0054-0.0400+ | Jones & Scarseth 1944 |
| Mn | A | ——— | G or H | Leaves | <0.0015-0.0402 | 0.0032-0.0240 | ——— | Lundegårdh 1931, 1932 |
| Mn | $B_1$ | ——— | J | Leaves | 0.0005 | 0.0012 | ——— | Albert 1932 |
| Mn | A | Flowering | G | Tops (?) | 0.00102-0.00143 | 0.00204-0.00820 | ——— | Samuel & Piper 1929 |
| Mn | E | Just after flowering | K | Tops | 0.00062-0.00127 | 0.00139-0.0111 | ——— | Samuel & Piper 1929 |
| Mn | C | 11 weeks | I | Plant | 0.00105 | 0.0064-0.0140 (Q) | ——— | Samuel & Piper 1928 |
| Mn | C | Harvest | I | Plant | 0.0009 | 0.0025-0.0054 (Q) | ——— | Samuel & Piper 1928 |
| Mn | C | Flowering | I | Plant | 0.00048-0.00099 | 0.00089-0.00567 | ——— | Piper 1931 |
| Cu | $B_1$ | Harvest | I | Straw | 0.000310-0.000506 | 0.000525-0.000699 | ——— | Rademacher 1937 |
| Cu | E | Harvest | I | Tops | 0.00009-0.00025 | 0.00011-0.00088 | ——— | Piper 1942 |
| Cu | $B_1$ | Harvest | I | Plant (?) | 0.00019 | 0.00019-0.00037 | ——— | Teakle *et al.* 1940 |
| OLIVE (*Olea europaea*) | | | | | | | | |
| B | A, $B_2$, C | ——— | K, L | Leaves | 0.0007-0.0013 | 0.0014-0.0180 (Q) | 0.0268 | Hansen 1945 |
| ONION (*Allium cepa*) | | | | | | | | |
| B | D | Apr.-Sept. | I | Leaves | ——— | 0.0029-0.0044 | 0.0091-0.1578 | Eaton 1944 |
| B | D | Apr.-Sept. | I | Roots | ——— | 0.0023-0.0028 | 0.0021-0.0346 | Eaton 1944 |
| B | D | Apr.-Sept. | I | Plant | ——— | 0.0027-0.0033 | 0.0058-0.1186 | Eaton 1944 |
| ORANGE (*Citrus aurantium, sinensis* etc.) [*see also* Citrus] | | | | | | | | |
| K | D | Oct. | J | Leaves | 0.46-0.55 | 1.71-2.72 | ——— | Cullinan *et al.* 1939 |
| K | A | ——— | K | Leaves | 0.59-0.93 | 1.5-2.44 | ——— | Cullinan *et al.* 1939 |
| K | D | Oct. | I | Leaves | 0.06-0.25 | 2.05-3.45 | ——— | Chapman & Brown 1943 |
| Ca | D | Sept. | J | Leaves | 0.14-0.20 | 1.48 | ——— | Reed & Haas 1923 |
| Ca | D | Sept. | J | Shoots | 0.23-0.28 | 1.17 | ——— | Reed & Haas 1923 |
| Ca | D | Sept. | J | Trunk | 0.62-0.66 | 0.63 | ——— | Reed & Haas 1923 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled. | Part of plant | Percentage of element in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| ORANGE (*Citrus aurantium, sinensis* etc.) [*see also* Citrus]—continued | | | | | | | | | |
| | Ca | D | Sept. | J | Roots | 0.42 | 0.50 | ——— | Reed & Haas 1923 |
| | Ca | D | Sept. | J | Rootlets | 0.29-0.36 | 2.00 | ——— | Reed & Haas 1923 |
| | Mg | A | Nov. | K | Mature leaf laminae | 0.026-0.128 | 0.172-0.518 | ——— | Parbery 1935 |
| | S | C, D | ——— | K | Young terminal leaves | 0.075-0.096 | 0.189-0.260 | ——— | Chapman & Brown 1941a |
| | S | C, D | ——— | K | Old leaves | 0.120-0.129 | 0.220-0.320 | ——— | Chapman & Brown 1941a |
| | S | A, D | ——— | I | Twigs | 0.014 | 0.029 | ——— | Haas 1936 |
| | S | A, D | ——— | I | Trunk bark | 0.031-0.036 | 0.017-0.077 | ——— | Haas 1936 |
| | S | A, D | ——— | I | Rootlets | 0.066 | 0.079 | ——— | Haas 1936 |
| | B | A | ——— | K | Leaves | ——— | 0.0035-0.0522 | 0.0558-0.1062 | Scofield & Wilcox 1931 |
| | B | A, $B_1$ | ——— | K | Leaves | ——— | 0.0021-0.0087 | 0.0463-0.1679 | Kelley & Brown 1928 |
| | B | A | May | G | Leaves | 0.00043-0.00128 | 0.00145-0.00184 | ——— | Morris 1938 |
| | B | A, $B_1$ | Jan.-July | I | Young and mature fruit | 0.00049-0.00090 | 0.00063-0.00258 | ——— | Morris 1938 |
| | Mn | D | ——— | J | Leaves | 0.0007-0.0010 | 0.0018-0.0020 | ——— | Chapman *et al.* 1939 |
| | Mn | A, $B_3$ | ——— | K | Leaves | 0.00044-0.00111 | 0.00208-0.00294 | ——— | Levitt & Nicholson 1941 |
| PARSLEY (*Petroselinum hortense*) | | | | | | | | | |
| | B | D | Mar. | I | Plant | ——— | 0.0016-0.0388 | 0.0588-0.0890 | Eaton 1944 |
| PEA (*Pisum sativum*) | | | | | | | | | |
| | P | D | Flowering | I | Stems (2% acetic acid extract) | 0.0015.-0.0046 (O) | 0.0156-0.0500 (O) | ——— | Hill 1943 |
| | K | A, $B_1$ | ——— | H, I | Foliage | 0.21-0.25 | 0.50 | ——— | Brickley 1943 |
| | K | A | ——— | J | Lower stems (2% acetic acid extract) | 0.004-0.033 (O) | 0.500 (O) | ——— | Carolus 1938. Carolus *et al.* 1938 |
| | K | D | Flowering | I | Stems (2% acetic acid extract) | 0.218-0.381 (O) | 0.762 (O) | ——— | Hill 1943 |
| | B | D | May | I | Leaves | ——— | 0.0016-0.0212 | 0.0609-0.1452 | Eaton 1944 |
| | B | D | Mar.-May | I | Plant | ——— | 0.0016-0.0064 | 0.0110-0.0867 | Eaton 1944 |
| | Mn | A | Harvest | J | Seeds | 0.00037-0.00050 | 0.00037-0.00075 | ——— | Löhnis 1936 |
| | Mn | A | Harvest | K | Seeds (different parts) | 0.0002-0.0005 | 0.0004-0.0015 | ——— | Glasscock & Wain 1940 |
| | Mn | $B_3$, C | Harvest | I, L | Seeds | 0.00122-0.00217 | 0.00160-0.00264 | ——— | Walsh & Cullinan 1945 |
| PEACH *Prunus persica*) | | | | | | | | | |
| | K | D | Oct. | J | Leaves | 0.46-0.55 | 1.71-2.72 | ——— | Cullinan *et al.* 1939 |
| | K | A | ——— | K | Leaves | 0.59-0.93 | 1.50-2.44 | ——— | Cullinan *et al.* 1939 |
| | K | $B_1$ | Late summer | I | Leaves from middle of current season's growth | 0.64-1.95 | 2.05-2.82 | ——— | Cullinan & Waugh 1940 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| K | A | Summer | K | Leaves from middle of current season's growth | 0.50-0.84 | 1.26-2.78 (Q) | ———— | Cullinan & Waugh 1940 |
| K | $B_1$ | ———— | J | Leaves | 0.59-1.35 | 1.58-2.65 | ———— | Cullinan & Batjer 1943 |
| K | D | Sept. | I | Stems (apical 6"—acetate buffer extract) | 0.0200-0.1100 (O) | 0.1125-0.5500 (O) | ———— | Davidson & Blake 1938 |
| Ca | D | Sept. | I | Stems (apical 6"—acetate buffer extract) | 0.0070-0.0175 (O) | 0.0300-0.0525 (O) | ———— | Davidson & Blake 1938 |
| B | D | Nov. | I | Leaves | ———— | 0.0017-0.0081 | 0.0170 | Eaton 1944 |
| B | D | Nov. | I | Stems | ———— | 0.0007-0.0044 | 0.0138 | Eaton 1944 |
| B | D | Nov. | I | Roots | ———— | 0.0002-0.0053 | 0.0192 | Eaton 1944 |
| Mn | A | June-July | G | Mature basal leaves on current growth | 0.00055-0.00193 | 0.00177-0.03246 | ———— | Epstein & Lilleland 1942 |
| Zn | A, B | Sept.-Oct. | K | Leaves (of apical 6"—8") | 0.0006-0.0015 | 0.0006-0.0043 | ———— | Chandler *et al.* 1934 |
| Zn | A, B | Sept.-Oct. | K | Stems (apical 6"—8") | 0.0005-0.0012 | 0.0011-0.0050 | ———— | Chandler *et al.* 1934 |
| As | A | Summer | K | Leaves | | 0.00009-0.00013 | 0.00013-0.00052 | Lindner 1943 |
| **PEANUT** (*Arachis hypogaea*) | | | | | | | | |
| P | D | ———— | I | Leaves | 0.01 (M) | 0.02-0.04 (M) | ———— | Burkhart & Collins 1942 |
| K | D | ———— | I | Leaves | 0.01 (M) | 0.21-0.68 (M) | ———— | Burkhart & Collins, 1942 |
| Ca | D | ———— | I | Leaves | 0.02 (M) | 0.17-0.51 (M) | ———— | Burkhart & Collins 1942 |
| Mg | D | ———— | I | Leaves | 0.01 (M) | 0.10-0.17 (M) | ———— | Burkhart & Collins 1942 |
| **PEAR** (*Pyrus communis* etc.) | | | | | | | | |
| K | A | Aug. | J | Leaves from middle of terminal shoots | 0.43 | 1.07 | ———— | Reuther 1941a |
| Cu | A | June-Oct. | H | Leaves | 0.00031-0.00051 | 0.00056-0.00200 | ———— | Oserkowsky & Thomas 1933 |
| Cu | A | ———— | H | Leaves | 0.00032-0.00067 | 0.00049-0.0041 | ———— | Oserkowsky & Thomas 1938 |
| Cu | A, B | June-July | H | Wood | 0.00012-0.00046 | 0.00018-0.00116 | ———— | Oserkowsky & Thomas 1938 |
| Cu | A, B | June-July | H | Bark | 0.00030-0.00042 | 0.00037-0.00166 | ———— | Oserkowsky & Thomas 1938 |
| **PECAN** (*Carya pecan*) | | | | | | | | |
| Zn | A, B | Aug. | K | Leaflets | 0.00037 | 0.00039-0.00167 | ———— | Finch & Kinnison 1933 |
| Zn | A | Oct. | K | Leaves at top of tree | Trace-0.0071 | 0.0066-0.0202 | ———— | Finch 1936 |
| Zn | A, B | Aug. | K | Petioles | Trace | Trace-0.00100 | ———— | Finch & Kinnison 1933 |
| Zn | A, B | Aug. | K | Shoots | Trace | 0.00079-0.00153 | ———— | Finch & Kinnison 1933 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of element in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| PINE (*Pinus* spp.) | | | | | | | | | |
| | Mg | A | ——— | J | Leaves | 0.078-0.095. | 0.115-0.176 | ——— | Němec 1942 |
| | Mg | A | ——— | J | Wood | 0.059-0.133 | 0.063-0.140 | ——— | Němec 1942 |
| PINEAPPLE (*Ananas sativus*) | | | | | | | | | |
| | Zn | A | Various | J | Leaf bases | 0.0004-0.0026 | 0.0016-0.0044 | ——— | Lyman & Dean 1942 |
| | Zn | A | Various | J | Distal parts of leaves | 0.0004-0.0026 | 0.0004-0.0026 | | Lyman & Dean 1942 |
| | Zn | A | Various | J | Stem growing points | 0.0006-0.0096 | 0.0144-0.0158 | ——— | Lyman & Dean 1942 |
| PLUM (*Prunus domestica* etc.) | | | | | | | | | |
| | K | A | July | I | Spur leaf laminae | 0.22-0.66 | 0.77-2.57 | ——— | Wallace 1928b |
| | K | A | ——— | H | Leaves | 0.22-1.11 | 1.47-2.00 | ——— | Wallace 1931 |
| | K | A | Aug.-Sept. | J | Leaves from middle of terminal shoots | 0.32-1.82 | 0.84-3.30 (Q) | ——— | Reuther 1941a |
| | K | A | ——— | H | Fruit pulp | 0.35-0.97 | 0.55-1.45 | ——— | Wallace 1931 |
| | Mg | A | Sept. | I | Leaves from base of terminal shoots | 0.14 | 0.18 | ——— | Wallace 1940 |
| | B | A | Oct. | J | Leaves | ——— | 0.0033 | 0.0176 | Eaton, F. M. 1935 |
| | B | A | Oct. | J | Twig bark | ——— | 0.0036 | 0.0412 | Eaton, F. M. 1935 |
| | B | A | Oct. | J | Twig wood | ——— | 0.0011 | 0.0171 | Eaton, F. M. 1935 |
| | Mn | A | ——— | J | Basal leaves on current growth | 0.0015 | 0.00553-0.00926 | ——— | Epstein & Lilleland 1942 |
| | Cu | $A,B_I$ | ——— | J | Apical leaves | 0.00032-0.000425 | 0.000717-0.000952 | ——— | Anderssen 1932 |
| POTATO (*Solanum tuberosum*) | | | | | | | | | |
| | K | $B_I$ | July | I | Leaves | 2.90-3.51 | 5.85-6.79 | ——— | Jones & Plant 1943 |
| | K | A | July-Aug. | J | Upper leaves | 1.2-2.1 | 2.1-3.8 | ——— | Large 1945 |
| | K | $B_I$ | ——— | I | Leaves | 1.55-3.19 | 5.19-6.36 | ——— | Nicholas & Jones 1945 |
| | K | $A,B_I$ | ——— | H | Foliage | 0.38-0.44 | 1.00 | ——— | Brickley, 1943 |
| | Mg | A | May-June | J | Upper leaves | 0.122-0.218 | 0.231-0.296 | ——— | Carolus 1933 |
| | Mg | A | May-June | J | Lower leaves | 0.043-0.124 | 0.159-0.251 | ——— | Carolus 1933 |
| | Mg | $B_I$ | Aug. | I | Leaves | 0.10-0.20 | 0.37-0.40 | ——— | Wallace *et al.* 1942 |
| | Mg | $B_I$ | July | I | Leaves | 0.16-0.33 | 0.40-0.86 | ——— | Jones & Plant 1943 |
| | Mg | $B_I$ | ——— | I | Leaves | 0.22-0.24 | 0.40-0.78 | ——— | Nicholas & Jones 1945 |
| | Mg | C | ——— | I | Foliage | 0.124-0.287 | 0.279-0.662 | ——— | Carolus 1934 |
| | Mg | A | May | J | Stems | 0.135-0.138 | 0.163-0.166 | ——— | Carolus 1933 |
| | Mg | $B_I$ | Aug. | I | Stems | 0.20-0.30 | 0.61-0.62 | ——— | Wallace *et al.* 1942 |
| | Mg | A | May | J | Tops | 0.065-0.115 | 0.220-0.290 | ——— | Carolus 1933 |
| | Mg | $B_I$ | ——— | I | Tubers | 0.12 | 0.13 | ——— | Garner *et al.* 1930 |
| | Mg | C | May | I | Plant | 0.069-0.133 | 0.290-0.495 | ——— | Carolus & Brown 1935 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| RADISH (*Raphanus sativus*) | | | | | | | | |
| B | D | Feb.-Nov. | I | Leaves | 0.0008-0.0033 | 0.0019-0.0195 | 0.0086-0.1151 | Eaton 1944 |
| B | D | Feb.-Nov. | I | Roots | 0.0015-0.0033 | 0.0013-0.0059 | 0.0062-0.0183 | Eaton 1944 |
| B | D | Feb.-Nov. | I | Plant | 0.0022-0.0027 | 0.0019-0.0134 | 0.0078-0.0724 | Eaton 1944 |
| RED CABBAGE (*Brassica oleracea* var.) | | | | | | | | |
| B | A, $B_1$ | ——— | J, K | Leaves | 0.0007-0.0015 | 0.0020-0.0030 | ——— | Maier 1944 |
| RED CURRANT (*Ribes sativum*) | | | | | | | | |
| K | $B_1$ | June | K | Leaf laminae | 0.24-0.99 | 0.90-1.59 | ——— | Boresch 1938 |
| K | C | ——— | K | Leaf laminae | 0.35-1.45 | 0.89-3.16 | ——— | Boresch 1938 |
| RED PEPPER (*Capsicum frutescens*) | | | | | | | | |
| B | D | Oct. | I | Leaves | ——— | 0.0034-0.0118 | 0.0328-0.0882 | Eaton 1944 |
| B | D | Oct. | I | Fruit | ——— | 0.0021 | 0.0016-0.0046 | Eaton 1944 |
| B | D | Oct. | I | Plant | ——— | 0.0019 | 0.0024-0.0048 | Eaton 1944 |
| RHUBARB (*Rheum rhaponticum*) | | | | | | | | |
| K | A | ——— | J | Petioles (2% acetic acid extract) | 0.1080 (O) | 0.3980 (O) | ——— | Carolus 1936, 1938, 1938a |
| RICE (*Oryza sativa*) [*see also* Cereals] | | | | | | | | |
| S | $B_1$ | Dec.-Jan. | K | Straw | 0.053-0.062 | 0.100-0.118 | ——— | Sen 1938a |
| S | A, $B_1$ | Harvest | K | Straw | 0.049-0.064 | 0.118-0.138 | ——— | Aiyar 1945 |
| S | $B_1$ | Dec.-Jan. | K | Grain | 0.096-0.105 | 0.114-0.126 | ——— | Sen 1938a |
| S | A, $B_1$ | Harvest | K | Grain | 0.080-0.094 | 0.115-0.138 | ——— | Aiyar 1945 |
| S | $B_1$ | Sept. | K | Plant | 0.034-0.040 | 0.065-0.125 | ——— | Sen 1938a |
| RYE (*Secale cereale*) | | | | | | | | |
| Mg | A, C | Apr.-May | I | Plant (?) | 0.12-0.34 | 0.19-0.56 | ——— | van Itallie 1936 |
| Cu | $B_1$ | ——— | J | Grain | <0.00005 | <0.0002 | ——— | Sjollema 1933 |
| SAVOY CABBAGE (*Brassica oleracea* var.) | | | | | | | | |
| B | A, $B_1$ | ——— | I | Leaves | 0.0008 | 0.0015-0.0035 (Q) | ——— | Maier 1944 |
| SOYBEAN (*Glycine soja*) [*see also* Tables XIII, XIV] | | | | | | | | |
| Mg | $B_1$ | ——— | I | Plant | 0.30 | 0.59 | ——— | Garner *et al.* 1930 |
| Mn | E | 30 days after germination | I | Leaves | See Table XIII | See Table XIII | | Somers & Shive 1942 |
| Mn | E | 30 days after germination | I | Roots | ,, | ,, | | Somers & Shive 1942 |
| SPINACH (*Spinacia oleracea*) | | | | | | | | |
| Mn | $B_3$ | Harvest (June) | I | Plant | 0.00233 | 0.00342-0.00600 | ——— | Gilbert *et al.* 1926 |
| Mn | $B_3$ | Harvest (Oct.) | I | Plant | 0.00518 | 0.00561-0.01030 | ——— | Gilbert *et al.* 1926 |
| Mn | A | ——— | J | Stem & petioles (?) (2% acetic acid extract) | 0.0012 (O) | 0.0031(O) | ——— | Carolus 1936 |
| STRAWBERRY (*Fragaria chiloensis, etc.*) | | | | | | | | |
| P | D | Jan.-Feb. | I | Leaves | 0.0072-0.0075 (O, M) | 0.098-0.320 (O, M) | ——— | Lineberry & Burkhart 1944 |
| P | $B_1$ | June | I | Crown leaves | 0.05-0.09 (M) | 0.10-0.18 (M) | ——— | Lineberry *et al.* 1944 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of element in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| STRAWBERRY (*Fragaria chiloensis, etc.*)—continued | | | | | | | | | |
| | P | $B_1$ | June | I | Mature crown leaves | 0.19 | 0.28-0.30 | ——— | Lineberry *et al.* 1944 |
| | P | D | Jan.-Feb. | I | Fruit | 0.0020-0.0039 (O, M) | 0.0039-0.0112 (O, M) | ——— | Lineberry & Burkhart 1944 |
| | K | D | Jan.-Feb. | I | Leaves | 0.10 (O, M) | 0.32-1.00 (O, M) | ——— | Lineberry & Burkhart 1944 |
| | K | D | Jan.-Feb. | I | Fruit | 0.027-0.051 (O, M) | 0.107-0.210 (O, M) | ——— | Lineberry & Burkhart 1944 |
| | Ca | D | Jan.-Feb. | I | Leaves | 0.10 (O, M, S.) | 0.48-0.70 (O, M, S) | ——— | Lineberry & Burkhart 1944 |
| | Ca | D | Jan.-Feb. | I | Leaves | 0.038 (O, M, R) | 0.082-0.138 (O, M, R) | ——— | Lineberry & Burkhart 1944 |
| | Ca | D | Jan.-Feb. | I | Fruit | 0.009 (O, M, S) | 0.011-0.032 (O, M, S) | ——— | Lineberry & Burkhart 1944 |
| | Ca | D | Jan.-Feb. | I | Fruit | 0.005 (O, M, R) | 0.009-0.020 (O, M, R) | ——— | Lineberry & Burkhart 1944 |
| | Mg | D | Jan.-Feb. | I | Leaves | 0.024-0.040 (O, M) | 0.20-0.51 (O, M) | ——— | Lineberry & Burkhart 1944 |
| | Mg | D | Jan.-Feb. | I | Fruit | 0.003-0.008 (O, M) | 0.009-0.025 (O, M) | ——— | Lineberry & Burkhart 1944 |
| | B | D | Mar. | I | Plant | | 0.0044-0.0113 | 0.0315-0.0755 | Eaton 1944 |
| SUGAR BEET (*Beta vulgaris* var.) [*see also* Beet] | | | | | | | | | |
| | K | A | ——— | J | Leaves | 0.43-0.98 | 0.94-8.00 | ——— | Hale 1945 |
| | Mg | A | ——— | J | Leaves | 0.08-0.20 | 0.21-1.70 | ——— | Hale 1945 |
| | B | A | ——— | J | Leaves | 0.0004-0.0028 | 0.0025-0.0052 | ——— | Brandenburg 1939 |
| | B | D | Aug.-Sept. | I | Leaf laminae | 0.0019-0.0035 | 0.0020-0.0426 | 0.0495-0.1008 | Eaton 1944 |
| | B | A | ——— | J | Leaves | 0.0006-0.0013 | 0.0010-0.0044 | ——— | Hale 1945 |
| | B | $B_1$ | Oct. | I | Roots | 0.00111-0.00124 | 0.00124-0.00135 | ——— | Brandenburg 1932a |
| | B | A | ——— | J | Roots | 0.0013-0.0014 | 0.0013-0.0015 | ——— | Brandenburg 1939 |
| | B | A | ——— | J | Roots | 0.035-0.052 (N) | 0.053-0.066 (N) | ——— | Brandenburg 1939 |
| | B | D | Aug. Sept. | I | Roots | 0.0006-0.0020 | 0.0002-0.0028 | 0.0028-0.0052 | Eaton 1944 |
| | B | D | Aug.-Sept. | I | Plant | 0.0013-0.0033 | 0.0010-0.0139 | 0.0147-0.0354 | Eaton 1944 |
| | Mn | A | ——— | J | Leaves | 0.0005-0.0030 | 0.0007-0.1700 | 0.125-0.302 | Hale 1945 |
| SUGAR CANE (*Saccharum officinarum*) | | | | | | | | | |
| | Mn | A (?) | ——— | K | Leaves | Trace—0.0005 | 0.003 | ——— | Lee & McHargue 1928 |
| | Cl | A | ——— | I | Plant | ——— | 10.83 (N) | 15.75 (N) | Follett-Smith 1934, 1939 |
| SUNFLOWER (*Helianthus annuus*) | | | | | | | | | |
| | B | C | 6 weeks | I | Tops | 0.0008-0.0023 | 0.0012-0.0150 | ——— | Tanada & Dean 1942 |
| | B | C | 6 weeks | I | Tops | ——— | 0.0012-0.0150 | 0.0200-0.0360 | Tanada & Dean 1942 |
| SWEDE (*Brassica napus*) | | | | | | | | | |
| | B | A, $B_1$ | ——— | J | Leaves | 0.0018-0.0029 | 0.0030-0.0066 | ——— | Brandenburg 1939 |
| | B | A, $B_1$ | ——— | J | Roots | 0.0012-0.0015 | 0.0018-0.0026 | ——— | Brandenburg 1939 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SWEET CLOVER (*Melilotus indica*) | | | | | | | | |
| B | D | Apr.-Aug. | I | Leaves | ——— | 0.0058-0.0665 | 0.0602-0.2245 | Eaton 1944 |
| B | D | Apr.-Aug. | I | Plant | ——— | 0.0026-0.0265 | 0.0264-0.0912 | Eaton 1944 |
| SWEET PEA (*Lathyrus odoratus*) | | | | | | | | |
| B | D | Apr. | I | Leaves | 0.0030 | 0.0190 | 0.0520-0.1551 | Eaton 1944 |
| B | D | Apr. | I | Seeds | 0.0001 | 0.0018 | 0.0050-0.0055 | Eaton 1944 |
| B | D | Apr. | I | Plant | 0.0032 | 0.0085 | 0.0211-0.0664 | Eaton 1944 |
| SWEET POTATO (*Ipomoea batatas*) | | | | | | | | |
| Mg | $B_1$ | ——— | I | Leaves | 0.40 | 0.71 | ——— | Garner *et al.* 1930 |
| Mg | $B_1$ | ——— | I | Tubers | 0.06 | 0.06 | ——— | Garner *et al.* 1930 |
| B | D | Oct. | I | Tops | 0.0016 | 0.0118 | 0.0310-0.1410 | Eaton 1944 |
| B | D | Oct. | I | Roots | 0.0006 | 0.0044 | 0.0020-0.0090 | Eaton 1944 |
| B | D | Oct. | I | Plant | 0.0013 | 0.0098 | 0.0228-0.1083 | Eaton 1944 |
| TEA (*Thea sinensis*) | | | | | | | | |
| K | A | ——— | J | Leaves | 0.24-0.59 | 0.66-1.59 | ——— | de Haan & Schoorel 1940 |
| TOBACCO (*Nicotiana tabacum*) [*see also* Table XIV] | | | | | | | | |
| K | A | Sept. | J | Leaves | 2.79-3.72 | 4.37-5.29 | ——— | Lagatu & Maume 1935e |
| Mg | $B_1$ | ——— | I | Leaves | 0.08-0.21 | 0.18-0.65 | ——— | Garner *et al.* 1930 |
| Mg | $B_1$ | ——— | I | Stems | 0.14-0.24 | 0.11-0.31 | ——— | Garner *et al.* 1930 |
| Ca | $B_1$ | ——— | H, I | Leaves | 0.94-1.30 | 1.33-2.43 | ——— | Garner *et al.* 1930 |
| B | D | Aug. | I | Leaf laminae | | 0.0019-0.0261 | 0.0365-0.0771 | Eaton 1944 |
| B | C | ——— | I | Plant | See Table XIV | See Table XIV | | Drake *et al.* 1941; Jones & Scarseth 1944 |
| B | D | Aug. | I | Plant | ——— | 0.0022-0.0117 | 0.0152-0.0335 | Eaton 1944 |
| Mn | — | ——— | J | Leaves | ——— | 0.016 | 0.400-1.100 | Jacobson & Swanback 1932 |
| Mn | — | ——— | J | Roots | ——— | 0.016 | 0.317 | Jacobson & Swanback 1932 |
| Mn | C, E | Apr. | K | Plant | ——— | Trace-0.0334 (Q) | 0.0933-1.130 | Bortner 1935 |
| TOMATO (*Lycopersicum esculentum*) | | | | | | | | |
| P | D | 50 days | I | Leaves | 0.238-0.354 | 0.420-0.724 | ——— | Kalin 1943 |
| P | D | 50 days | I | Stems | 0.200-0.246 | 0.302-0.546 | ——— | Kalin 1943 |
| K | D | Apr.-May | I | Leaves | 1.04-1.23 | 1.55-3.76 | ——— | Wall 1939 |
| K | D | Apr.-May | I | Leaves | 0.28-1.44 | 1.40-2.40 | ——— | Wall 1940a, 1940b |
| K | D | Apr.-May | I | Stems | 0.86-1.06 | 1.55-5.30 | ——— | Wall 1939 |
| K | D | Apr.-May | I | Lower stems | 0.16-1.04 | 1.40-2.32 | ——— | Wall 1940a, 1940b |
| K | D | May | I | Fruit | 1.52-2.40 | 4.00 | ——— | Wall 1940a, 1940b |
| Mg | A | ——— | J | Leaf laminae | 0.10 | 0.42 | ——— | Cromwell & Hunter 1942 |
| B | D | July-Aug. | I | Leaves | ——— | 0.0034-0.0150 | 0.0253-0.1416 | Eaton 1944 |
| B | D | July | I | Fruit | ——— | 0.0024-0.0027 | 0.0060-0.0131 | Eaton 1944 |
| B | D | July-Aug. | I | Plant | ——— | 0.0029-0.0078 | 0.0148-0.0709 | Eaton 1944 |
| B | D | ——— | I | Plant | 0.0014-0.0032 (T) | 0.0034-0.0096 (T) | 0.0091-0.0415 (T) | Reeve & Shive 1943 |
| Mn | E | Oct. | I | Leaflets | 0.00053-0.00056 | 0.00697-0.03980 | ——— | Lyon *et al.* 1943 |
| Mn | E | Harvest | I | Fruit | 0.00002 | 0.00017 | ——— | Lyon *et al.* 1943 |

| Plant spp. | Element | Conditions of growth | Date or stage of development | Unit sampled | Part of plant | Percentage of element in dry matter, unless otherwise indicated: Shewing deficiency symptoms | Without symptoms | Shewing toxicity symptoms | Reference |
|---|---|---|---|---|---|---|---|---|---|
| TOMATO (*Lycopersicum esculentum*)—continued | | | | | | | | | |
| | Zn | E | Oct. | I | Leaflets | 0.00144-0.00234 | 0.00269-0.00298 | ——— | Lyon *et al.* 1943 |
| | Zn | E | Harvest | I | Fruit | 0.00006 | 0.00019 | ——— | Lyon *et al.* 1943 |
| TUNG (*Aleurites* spp.) | | | | | | | | | |
| | K | A | Sept. | G | Middle leaves from non-fruiting terminals | 0.24-0.64 | 0.61-1.01 | ——— | Drosdoff & Painter 1942 |
| | K | $B_1$ | ——— | I | Leaves | 0.41-0.74 | 0.70-0.92 | ——— | Painter & Drosdoff 1943 |
| | Mg | A, $B_1$ | Oct. | K | Leaves | 0.05-0.16 | 0.20-0.35 (Q) | ——— | Drosdoff & Kenworthy 1944 |
| | Mn | $B_1$ | Aug. | I | Leaves | 0.0025-0.0122 | 0.0322 (Q) | ——— | Dickey and Drosdoff 1943 |
| | Mn | $B_1$ | July-Oct. | G | Middle leaves from non-fruiting terminals | 0.0058-0.0081 | 0.0638-0.3110 | ——— | Drosdoff 1944 |
| | Cu | A, B | Aug. | J | Leaves | 0.00026-0.00031 | 0.00048-0.00057 | ——— | Drosdoff & Dickey 1943 |
| | Zn | A, $B_1$ | ——— | I | Leaves | 0.00036-0.00062 | 0.00157-0.00358 | ——— | Gaddum *et al.* 1937 |
| | Zn | A, $B_1$ | ——— | I | Petioles | 0.00037-0.00040 | 0.00091-0.00284 | ——— | Gaddum *et al.* 1937 |
| TURNIP (*Brassica rapa*) | | | | | | | | | |
| | B | D | May | I | Leaves | ——— | 0.0016-0.0213 | 0.0399 | Eaton 1944 |
| | B | A | ——— | G | Roots | 0.00047-0.00169 | 0.00188 | ——— | Rigg *et al.* 1937 |
| | B | D | May | I | Roots | ——— | 0.0019-0.0065 | 0.0132 | Eaton 1944 |
| | B | D | May | I | Plant | ——— | 0.0017-0.0171 | 0.0349 | Eaton 1944 |
| WALNUT (*Juglans regia*) | | | | | | | | | |
| | B | A | ——— | G | Leaves | 0.0360-0.1018 | 0.0016-0.0112 | 0.0360-0.1018 | Kelley & Brown 1928 |
| | B | A | ——— | K | Leaves | ——— | 0.0108-0.0378 (Q) | 0.0432-0.1088 | Scofield & Wilcox 1931 |
| | Mn | A | ——— | J | Basal leaves of current growth | 0.0006-0.0025 | 0.02111-0.02712 | ——— | Epstein & Lilleland 1942 |
| | Mn | A | June | K, L | Leaves | 0.00050-0.00085 | 0.00350-0.00650 | ——— | Vanselow 1945 |
| | Zn | A | Sept.-Oct. | K | Leaves (of apical 6"—8") | 0.0011-0.0022 | 0.0016-0.0030 | ——— | Chandler *et al.* 1934 |
| | Zn | A | Sept.-Oct. | K | Stems (apical 6"—8") | 0.0008-0.0017 | 0.0024-0.0034 | ——— | Chandler *et al.* 1934 |
| WHEAT (*Triticum vulgare*) [*see also* Cereals] | | | | | | | | | |
| | Mg | A, C | Apr.-May | I | Plant (?) | 0.23-0.32 | 0.27-0.46 | ——— | van Itallie 1936 |
| | Mn | A | ——— | K | Plant | 0.0004-0.0010 | 0.0016-0.0028 | ——— | Gallagher & Walsh 1943 |
| | Cu | $B_1$ | ——— | J | Straw | 0.00085 | 0.0009-0.0018 | ——— | Sjollema 1933 |
| | Cu | $B_1$ | ——— | J | Grain | 0.00015 | 0.00030-0.00045 | ——— | Sjollema 1933 |

**NOTES**

*N.B.—Notes A—E refer to column 3, F to column 4, G—M to column 5 and N—T to columns 7—9.*

A. Field observations (plants not subjected to differential nutritional treatments).
B. Trial of different nutritional treatments in the field :
   $B_1$ by soil application,
   $B_2$ by injection,
   $B_3$ by spraying.
C. Pot culture trials with soil.
D. Sand culture trials.
E. Solution culture trials.
F. Observations in the Southern Hemisphere (only noted where time of year is stated).
G. District, orchard or field.
H. Part of orchard or field.
I. Group of plants with similar situation or treatment.
J. Group of plants selected on a basis of symptoms.
K. Plant.
L. Part of plant.
M. Soluble in water.
$M_1$. Insoluble in water.
N. % in ash.
O. % in fresh matter.
P. % in sap.
Q. Including some plants shewing slight symptoms.
R. Variety Blakemore.
S. Variety Klondike.
T. Read from graphs.

As Table I shews, the ranges of nutrient content for affected and unaffected plants are often fairly sharply separated, or have only a very small overlap. This has led many investigators to suggest limiting values, figures below which will normally correspond with the presence of deficiency symptoms, whereas plants appearing healthy will give higher values (and, *mutatis mutandis*, for toxicity disorders). A number of such limiting values are recorded in Table II ; others may be deduced by the reader from the composition ranges given in Table I. A few of the limiting values in Table II relate not to percentages of a nutrient in the plant material, but to ratios of nutrients, where the authority quoted considered that the incidence of symptoms of a deficiency depended on the ratio of the content of the deficient nutrient to that of another nutrient element rather than to the total dry matter. In some instances, the limiting value has been stated on a fresh matter or ash basis.

It has sometimes been suggested that the limiting value for appearance of symptoms of deficiency of one nutrient may be modified in accordance with the supply of another. For instance, Atterberg (1888a) in oats and Ulrich (1942) in the tomato have found lower limiting values for potassium when sodium supply is high than when it is low, and de Vries (1939) found that the pH of the substrate affected the relation between magnesium content and the incidence of magnesium deficiency symptoms.

## Table II

**Limiting values for nutrient content of plant material, below which the development of deficiency symptoms may be expected, or above which toxicity symptoms may occur.**

*N.B.—Letters in brackets refer to Notes at end of Table*

| Plant | Disorder | Date or stage of development | Part of plant | Limiting value (% in dry matter of element in question unless otherwise stated) | Reference |
|---|---|---|---|---|---|
| APPLE (*Pyrus malus*, etc.) | | | | | |
| | P deficiency | During growing season | Terminal 5″ of twig (acetate buffer extract) | 0.01 (H) | Davidson, in Hambidg 1941 |
| | K deficiency | ———— | Leaves | 0.75-1.00 | Reuther & Boynton, 1940 Boynton & Compton, 19 |
| | K deficiency | ———— | Leaves | 0.70 | Batjer & Magness, 1939 |
| | K deficiency | July-Aug. | Terminal shoot leaves | 0.83 (A) | Wallace, 1940, 1943; Wallace & Osmond, 19 |
| | K deficiency | ———— | Leaves | 1.00 | Cullinan & Batjer, 1943 |
| | K deficiency | July | Median shoot leaves | 1.00 (B) | Boynton *et al.* 1944 |
| | K deficiency | During growing season | Terminal 5″ of twig (acetate buffer extract) | 0.1 (H) | Davidson, in Hambidg 1941 |
| | Ca deficiency | During growing season | Terminal 5″ of twig (acetate buffer extract) | 0.1 (H) | Davidson, in Hambidge 1941 |
| | Ca deficiency | July-Aug. | Terminal shoot leaves | 0.72 | Wallace, 1939, 1940a, 194 |
| | Mg deficiency | July-Aug. | Terminal shoot leaves | 0.24 (A) | Wallace, 1939, 1940, 194 1943 |
| | Mg deficiency | During growing season | Terminal 5″ of twig (acetate buffer extract) | 0.006 (H) | Davidson, in Hambidg 1941 |
| | Mg deficiency | Aug. | Middle shoot leaves | 0.25 (C) | Southwick, 1943 |
| | Mg deficiency | Midsummer | Shoot leaves | 0.15-0.25 | Boynton & Compton, 194 |
| | Mg deficiency | July | Median shoot leaves | 0.20 | Boynton *et al.*, 1944 |
| | Mg deficiency | ———— | Shoot leaves | 0.20 | Boynton & Burrell, 1944a |
| | Zn deficiency | ———— | Leaves | 0.0123 | Archibald & Wann, 1942 |
| BLACK RASPBERRY (*Rubus occidentalis*) | | | | | |
| | K deficiency | ———— | Leaves | 0.20 (J) | Clark & Powers, 1945 |
| BOYSENBERRY (*Rubus* hyb.) | | | | | |
| | K deficiency | ———— | Leaves | 0.50 (J) | Clark & Powers, 1945 |
| CACAO (*Theobroma cacao*) | | | | | |
| | K deficiency | ———— | Leaves | $\frac{N}{K_2O}$ ratio 1.0 | Hardy, 1937 |
| | K deficiency | ———— | Leaves | $\frac{K_2O}{CaO}$ ratio 1.0 | Hardy, 1937 |
| CARROT (*Daucus carota*) | | | | | |
| | P deficiency | Active growth period | Petioles (2% acetic acid extract) | 0.0125 (H) | Hill, 1943 |
| CEREALS (*see also* Maize, Oats) | | | | | |
| | Mg deficiency | 4-5 leaf stage | Plant | 0.097 (E) | van Itallie, 1936 |
| CHERRY (*Prunus cerasus*, etc.) | | | | | |
| | K deficiency | Midsummer | Shoot leaves | 0.75-1.00 | Boynton & Compton, 194 |
| | Zn deficiency | ———— | Leaves | 0.0123 | Archibald & Wann, 1942 |
| CITRUS (*Citrus* spp.) | | [*see also* Grapefruit] | | | |
| | K deficiency | July-Sept. | Spring cycle leaves of fruit-bearing branches (D) | 0.2 | Chapman & Brown, 194 1943, 1943a; Chapman *et al.*, 1944 |

| Plant | Disorder | Date or stage of development | Part of Plant | Limiting value (% in dry matter of element in question unless otherwise stated) | Reference |
|---|---|---|---|---|---|
| CITRUS (*Citrus* spp.) [*see also* Grapefruit]—continued | | | | | |
| | K excess | July-Sept. | Spring cycle leaves of fruit-bearing branches (D) | 3.0 (Ca% low) | Chapman & Brown, 1942, 1943 |
| | Mg deficiency | Apr. | Spring flush foliage | 0.20 (E) | Fudge, 1942 |
| GRAPEFRUIT (*Citrus paradisi*) [*see also* Citrus] | | | | | |
| | Mg deficiency | Apr. | Leaves of spring growth | 0.2 (E, I) | Fudge, 1942b |
| LUCERNE (*Medicago sativa*) | | | | | |
| | B deficiency | ——— | Leaves | 0.0012 (C) | Dregne & Powers, 1942 |
| MAIZE (*Zea mays*) (*see also* Cereals) | | | | | |
| | K deficiency | ——— | Plant | $\frac{K}{Ca+Mg}$ equivalent ratio 0.2 (E) | Stanford *et al.*, 1942 |
| MANGOLD (*Beta vulgaris*) | | | | | |
| | B deficiency | ——— | Leaves | 0.0018 | Brandenburg, 1939 |
| OATS (*Avena sativa*) [*see also* Cereals] | | | | | |
| | K deficiency | Maturity | Straw | 0.83 (Na low) | Atterberg, 1888a |
| | | | | 0.31-0.32 (Na high) | Atterberg, 1888a |
| | Ca deficiency | Maturity | Straw | 0.072-0.129 | Atterberg, 1901 |
| | Mg deficiency | 4-5 leaf stage | Plant (?) | 0.097 (E) | van Itallie, 1937 |
| | B toxicity | Starting to head | Plant | $\frac{Ca}{B}$ ratio 200 | Jones & Scarseth, 1944 |
| | Mn deficiency | Flowering | Green parts | 0.0014 | Samuel & Piper, 1929 |
| | Cu deficiency | Maturity | Tops | 0.00010 | Piper, 1942 |
| PEA (*Pisum sativum*) | | | | | |
| | K deficiency | Flowering | Stems (2% acetic acid extract ?) | 0.25 (H) | Hill, 1943 |
| PEACH (*Prunus persica*) | | | | | |
| | P deficiency | During growing season | Terminal 6″ of twig (acetate buffer extract) | 0.01 (H) | Davidson, in Hambidge, 1941 |
| | K deficiency | ——— | Leaves | 1.00 (E) | Cullinan *et al.*, 1939 Cullinan & Batjer, 1942, 1943 |
| | K deficiency | Midsummer | Shoot leaves | 0.75-1.00 | Boynton & Compton, 1945 |
| | K deficiency | During growing season | Terminal 6″ of twig (acetate buffer extract) | 0.1 (H) | Davidson, in Hambidge, 1941 |
| | Ca deficiency | During growing season | Terminal 6″ of twig (acetate buffer extract) | 0.01 (H) | Davidson, in Hambidge, 1941 |
| | Mg deficiency | During growing season | Terminal 6″ of twig (acetate buffer extract) | 0.006 (H) | Davidson, in Hambidge, 1941 |
| | Zn deficiency | ——— | Leaves | 0.0123 | Archibald &Wann, 1942 |
| | As toxicity | ——— | Leaves | 0.0002 (F) | Lindner, 1943 |
| PLUM (*Prunus domestica*) | | | | | |
| | K deficiency | ——— | Leaves | 1.50-2.00 (G) | Boynton, 1942 |
| | K deficiency | Midsummer | Shoot leaves | 0.75-1.00 | Boynton & Compton, 1945 |
| | Zn deficiency | ——— | Leaves | 0.0123 | Archibald & Wann, 1942 |
| POTATO (*Solanum tuberosum*) | | | | | |
| | Mg deficiency | ——— | Tops | 0.24 | Carolus, 1934 ; Jones & Brown, in Hambidge, 1941 |

| Plant | Disorder | Date or stage of development | Part of Plant | Limiting value (% in dry matter of element in question unless otherwise stated) | Reference |
|---|---|---|---|---|---|
| RED CURRANT (*Ribes sativum*) | | | | | |
| | K deficiency | ——— | Leaves | 0.90 | Boresch, 1938 |
| | Cl toxicity | ——— | Leaves | $\frac{K}{Cl}$ ratio 1.0 | Boresch, 1938 |
| RICE (*Oryza sativa*) | | | | | |
| | S deficiency | ——— | Plant | 0.06 | Sen, 1938a |
| SOYA BEAN (*Glycine soya*) | | | | | |
| | B toxicity | Harvest | Plant | 0.0050-0.0060 | Muhr, 1941 |
| | B toxicity | ——— | Plant | 0.0200 | Hodgkiss *et al.*, 1942 |
| | Mn deficiency | ——— | Leaves (expressed sap) | $\frac{Fe}{Mn}$ ratio 2.5 | Somers & Shive, 1942 |
| | Mn toxicity | ——— | Leaves (expressed sap) | $\frac{Fe}{Mn}$ ratio 1.5 | Somers & Shive, 1942 |
| SUGAR BEET (*Beta vulgaris*) | | | | | |
| | K deficiency | ——— | Leaves | 0.83 | Hale, 1945 |
| | Mg deficiency | ——— | Leaves | 0.18 | Hale, 1945 |
| | B deficiency | ——— | Leaves | 0.00175 | Brandenburg, 1939 |
| TOBACCO (*Nicotiana tabacum*) | | | | | |
| | N deficiency | ——— | Cured leaves | 1.50 | Garner *et al.*, 1934 |
| | Ca deficiency | ——— | Upper leaves | 1.1-1.5 | Garner *et al.*, 1930 |
| | Ca deficiency | ——— | Leaves | > 1.00 | McMurtrey, 1931, 1932 |
| | Mg deficiency | ——— | Leaves | 0.25 | Garner *et al.*, 1930; McMurtrey, 1931, 1932 |
| | B deficiency | Flowering (?) | Plant | $\frac{Ca}{B}$ ratio 1340 | Drake *et al.*, 1941 |
| | B toxicity | ——— | Plant | $\frac{Ca}{B}$ ratio 1200 | Jones & Scarseth, 1944 |
| TOMATO (*Lycopersicum esculentum*) | | | | | |
| | P deficiency | ——— | Stem (acetate buffer extract) | 0.0022 (H) | Hester, 1941 |
| TUNG (*Aleurites* spp.) | | | | | |
| | K deficiency | ——— | Leaf laminae | 0.6 | Drosdoff & Painter, 1942; Drosdoff, 1943 |
| | Mn deficiency | Early part of season | Leaf laminae from middle of shoot | 0.0030 | Drosdoff, 1943 |
| | Zn deficiency | ——— | Leaf laminae | 0.0010 | Drosdoff, 1943 |
| WHITE CLOVER (*Trifolium repens*) | | | | | |
| | Mo deficiency | ——— | Tops | 0.0001 | Stephens & Oertel, 1943 |

**NOTES**

A. It is claimed that these figures also apply to other fruit plants.

B. McIntosh variety.

C. This value is stated to be *near* the critical level.

D. The leaf samples were taken from a height of 3′—7′.

E. Below this value, symptoms were "marked" or "severe".

F. This value applies only to leaves themselves showing injury.

G. This value applies only to leaves themselves showing *no* injury. If the nutrient content falls below this level other parts of the plant may be expected to show injury.

H. Per cent. of fresh matter.

I. Seedy varieties.

J. These values are quoted as "critical levels" without further explanation, but it appears that they are intended to relate to the development of deficiency symptoms.

**Interpretation of the Results of Field Trials.**

Next to be considered are those investigations principally concerned with the interpretation of the results of manurial trials. First let us exclude the very numerous experiments in which determinations of total uptake per unit area of ground have been made for the purpose of judging what proportion of the added fertilizers has been absorbed by the plant. These experiments deviate from the practice, with which we in general have to deal, of using the *concentration* of nutrients in the plant material as an index ; moreover the determination of uptake is so tiresome a process that it would be impracticable as a routine diagnostic procedure. Some investigators, however, have used the percentage composition of the plant material as an index of the nutritional status of the plots in fertilizer trials, and their work at least implies that such data are relevant to diagnosis of the nutritional requirements of plants of unknown history. They may therefore properly be considered here.

Foremost among these investigations are those of what we may describe as the " foliar diagnosis " school (for general accounts, see Jacob, 1929 ; Lagatu, 1940 ; Lagatu and Maume, 1934a, 1937, 1937b ; Thomas, 1945 ; Thomas and Mack, 1940a, 1944a ; Hibon, 1944). Lagatu and Maume at Montpellier from 1924 onwards published an extensive series of papers, first on the vine (Lagatu and Maume, 1924, 1924a, 1925, 1926, 1927, 1927a, 1927b, 1927c, 1927d, 1927e, 1928, 1928a, 1929, 1930, 1930d, 1930e, 1932, 1932b, 1933a, 1933b, 1933c, 1934, 1936, 1936a, 1936b, 1936d, 1936e, 1937a, 1937c, 1938, 1938a, 1938b, 1939, 1943 ; Lagatu *et al.*, 1932 ; Maume, 1942, 1944 ; Maume and Dulac, 1945), later on potato (Lagatu and Maume, 1929, 1930a, 1930b, 1930c, 1931, 1932a, 1932c, 1933, 1933a, 1934, 1934b, 1934c, 1935b, 1935c, 1935d, 1937c), tobacco (Lagatu and Maume, 1935, 1935a, 1935e, 1936c) and wheat (Maume and Dulac, 1934, 1934a, 1935, 1935a, 1936, 1936a, 1937, 1938, 1938a, 1942 ; Maume and Bouat, 1937) ; some years later, their ideas were adopted by Thomas in Pennsylvania (Thomas, 1929, 1930, 1932, 1934), who applied them to potatoes (Thomas, 1936, 1937, 1938, 1938a ; Thomas and Mack, 1938, 1939c, 1939d, 1939f, 1944), maize (Thomas, 1938b ; Thomas and Mack, 1939, 1939a, 1939b, 1939c, 1939e, 1943 ; Thomas *et al.*, 1943, 1944), tomato (Thomas and Mack, 1940, 1941, 1941a, 1941b, 1941c, 1941d, 1943a ; Thomas *et al.*, 1943a) and snap bean (Thomas *et al.*, 1942). A feature of the method is that the samples taken for analysis consist of leaves from a strictly defined morphological position—a procedure similar to that proposed by Remy (1903, 1903a) for hops—and similar samples are taken on several occasions during the growing season. An exception to this was made in the case of wheat, the samples for this plant consisting of the entire aerial parts gathered at definite stages of development. In interpreting the results of analysis of these samples, attention was concentrated not on the actual percentages of nutrients in the plant dry matter, but on their ratio. The nitrogen, "potash" and " phosphoric acid" contents were expressed each as a percentage of the total weight (Montpellier) or number of equivalents (Pennsylvania) of the three present in the material, and the proportions of the three bases potassium, calcium and magnesium were expressed in the same way. The nutritional status of the plant was then assessed in the main on the basis of these relative values—though at times the absolute percentages were also taken into account. Sometimes the course of change in the analytical data through the growing season was considered to be of importance ; at other times the " centre of gravity " of the relative values for successive samples from the same plot was used in place of the individual values.

These methods were used not only for interpreting the results of fertilizer trials, but also for elucidating the effects of disease, cultivation, irrigation and pruning treatments, and varying weather conditions. In addition, Lagatu and Maume (1935e, 1938a) appear to have used the method on occasion to indicate the cause of deficiency disorders of unknown origin. However, it is primarily as a tool of interpretation that the exponents of " foliar diagnosis " regard their method, and very few examples of their practical application in the field have been published. The point of view adopted seems to be that the "nutrition" of the plant is not governed only by the nutrients in the soil (Thomas and Mack, 1944a), or even by those taken up, but by the whole complex of environmental factors, so that the composition of the leaves and the changes in their composition during the growing season provide the most direct information on the "nutrition" of the plant available; the " foliar diagnosis" data do not themselves supply any information on how the mineral composition may be altered in such a way as to give higher yields (Lagatu and Maume, 1937).

The work of Lagatu and Thomas and their collaborators has proved stimulating to a number of agricultural chemists and plant physiologists, though—apart from Klemen (1931)—no other worker appears to have adopted the methods proposed in just their original form. Sandrock (1931) analysed leaves taken periodically from a defined position on the potato plant in the interpretation of a fertilizer trial. Vinet (Vinet, 1931, 1932, 1932a, 1933, 1934, 1935, 1937, 1938, 1942 ; Vinet and Lemesle, 1930, 1930a) applied the " *diagnostic foliaire* " of Lagatu and Maume to other fertilizer trials on vines ; but soon, instead of periodic sampling of leaves during the growing season he turned to a single sampling of shoot wood during the dormant season—a technique to which he gave the name " *diagnostic ligneux.*" Also, he did not adopt the form of expression in trilinear co-ordinates which characterized the Montpellier work but instead presented his results in the form of simple ratios. Beauchamp's work in Cuba was also influenced by the investigations in Pennsylvania and Montpellier ; he was concerned with the interpretation of fertilizer trials with sugar cane (Beauchamp, 1939 ; Beauchamp and Alvarino, 1940 ; Beauchamp and Lazo, 1938 ; Beauchamp *et al.*, 1934, 1935) and potato (Beauchamp 1940, 1942), but instead of the whole leaf material he analysed its alcohol extract ("crude chlorophyll") for the nutrient elements. The work on sugar cane in Mauritius (Halais, 1937 ; Craig, 1938, 1939, 1940, 1941, 1942 ; Craig and Halais, 1944 ; Evans, 1940, 1941) was also influenced by the investigations of Lagatu and Maume ; but here again the system of trilinear co-ordinates was abandoned, and the more fruitful approach was adopted of plotting actual percentages of nutrients in plant material against responses to fertilizer application.

Among the many other investigations in which plant analysis has been used primarily to interpret the results of field trials may be mentioned those by Wallace and his collaborators on gooseberry (Wallace, 1928a) and other fruit plants (Wallace and Osmond, 1941), potato (Wallace *et al.*, 1942 ; Jones and Plant, 1943) and tomato (Jones *et al.*, 1944) ; by Wagner (1931), Lilleland and his colleagues (Lilleland, 1931 ; Lilleland and Brown, 1940 ; Lilleland *et al.*, 1942), Baker (1936, 1941, 1943), Magness *et al.* (1940), Cullinan and Waugh (Cullinan and Waugh, 1940 ; Waugh and Cullinan, 1941), Reuther (1941), Boynton and his collaborators (Boynton, 1944 ; Boynton and Burrell, 1944 ; Boynton and Compton, 1944 ; Boynton *et al.*, 1941, 1943, 1944 ; Burrell *et al.*, 1942 ; Smock and Boynton, 1944), Kidson *et al.* (1943), Wander and Gourley (1943), Waltman (1944) and Southwick and his collaborators (Southwick and Shaw, 1944 ; Southwick and Smith, 1945) on tree fruits ; by Darrow and Magness (1939) on raspberries ; by the Trinidad investigators (McDonald, 1934 ; McDonald and Rodriguez, 1935 ; Hardy and Rodriguez, 1935 ; Hardy *et al.*, 1935) on cacao and grapefruit ; by Neller (1935) on sorghum, buckwheat and sugar cane ; by Němec (1938, 1939) on forest trees ; by Gilligan (1939) on sweet potatoes ; by Moser (1941, 1941a) on lespedeza, clover and peas ; by Martin (1940), Hilgeman *et al.* (1940) and Fudge (1941) on citrus ; by Chapman (1941) on rubber ; by Olson (1942) on cotton and maize ; by Ingram *et al.* (1943) on tomato ; by Davies *et al.* (1944) on potatoes ; and by Hirst and Greaves (1944) on sugar beet.

**Determination of Current Nutrient Requirements.**

We will now pass on to that group of diagnostic methods depending on the use of rapid chemical analyses, often called " tissue tests," and finding their principal application in advisory work though also widely used in the interpretation of the results of field trials. The tests have usually been carried out on sap or on extracts of fresh material from organs consisting largely of conducting tissue, the theory behind this being that the fractions estimated were mainly unassimilated materials which had recently entered the plant, and that their concentration thus represented the *current* rate of nutrient intake.

The series of tests most extensively used has been that developed at Purdue University, Indiana, mainly by Thornton, from 1926 onwards (Hoffer, 1926 ; Thornton, 1932, 1933, 1933a ; Thornton *et al.*, 1934 ; for general accounts of the technique, see also Scarseth, 1941a, 1941b, 1942, 1943). The technique only gave information on the three principal nutrients, and of the nitrogen in the extract only that in the form of nitrate was determined. The original investigations leading to the development of these tests were on maize, and maize has continued to be the principal interest of the Purdue workers (Thornton, 1932, 1933, 1933a ; Pettinger and Thornton, 1934 ; Cook, H.L., 1941, 1941a ; Drake, 1941, 1944 ; Ohlrogge, 1941, 1941a ; Vittum, 1941 ;

Scarseth, 1941, 1943, 1943a ; Scarseth *et al.*, 1943). Other plants studied there include potato (Thornton, 1933a), soybean (Thornton, 1933a; Scarseth, 1941), lawn grasses (Scarseth, 1941; Steckel, 1941), lucerne (Jones, 1941) and tomato (Ingram *et al.*, 1943). Investigators at a number of other centres have made use of the Indiana methods for their own problems. Shaw (1935) and Lilleland and Brown (1939) applied them to fruit tree petioles, Wark (1938, 1939) to cereals and peas, Ulrich (1941) to sugar beet petioles, Olson (1942, 1942a) to maize and cotton and Canadian workers (Atkinson *et al.*, 1944) to tomato, potato and sweet corn. The tests are only very roughly quantitative, and this is recognized in that the results are normally reported only in terms of four or five grades—though in his experiment on cotton Olson attempted to interpret them numerically.

Gilbert and his collaborators (Gilbert, 1926 ; Gilbert and Hardin, 1927 ; Gilbert *et al.*, 1927 ; Gilbert and Smith, 1929) proposed the use of analyses of expressed sap of a number of crop species as a means of control of their nutrition, and suggested several critical values (see Table XII). The sap composition was, however, found to be considerably affected by the weather, and after some years of trial the work appears to have been abandoned. Pettinger (1931) also used expressed sap of maize, and was able to suggest approximate limiting values.

Emmert (1932, 1935, 1935a, 1936, 1941, 1942a) carried out analyses for nitrate-nitrogen, phosphate-phosphorus and potassium, using 2% acetic acid extracts of fresh stems and petioles. The results were expressed numerically, and optimal or normal values were suggested for several crops (see Table XII). In the tomato (1941, 1942a) the optimal values were held to vary with the stage of development of the plant.

Morgan, in Connecticut, has been responsible for another series of tissue tests (1935, 1937). The tests were devised primarily for use on soil extracts, but it was claimed that they could also be applied to plant material extracted with the acetate buffer solution recommended. Morgan's methods have since found application to practical diagnostic work in Eire (Walsh, 1942), among other places.

Carolus (1938) also described a series of tests for the five principal nutrients to be used on 2% acetic acid extracts of plant tissue ; he put forward the view that the concentration of a nutrient in such an extract represented the current balance between its absorption and utilization—where the extract from a poorly growing plant contained a low concentration, the absorption of the nutrient was at fault, while if the concentration was unduly high its utilisation was inadequate. Carolus quoted limiting values for the potato (see Table XII) below which deficiency was to be suspected, and found, like Emmert, that these values changed during the course of development. The techniques proposed by Carolus were adopted by Hill (1943) at Ottawa ; previously (1938) when working at East Malling this investigator had made some use of the methods of Thornton, Emmert and Morgan, but apparently he found the methods developed in Virginia more satisfactory.

Hester (1941) is another worker who has described a system of " tissue tests." Tomato stems were extracted with an acetate buffer solution in a mechanical cocktail mixer ; limiting values for deficiency and normal ranges are given (see Table XII) for the content of nitrate-nitrogen, phosphate-phosphorus, and potassium. Like many other workers, however, Hester recommended comparison of the composition of the best and poorest plants in a field rather than reliance on limiting values.

Some interesting recent investigations in Hawaii, though not involving the use of rapid analytical techniques, have some affinity with those mentioned above in that they are attempts to assess the *current* nutrient needs of the plant with a view to immediate supply of the deficient materials. Work in Hawaii, on both sugar cane and pineapple, has been coloured and complicated by the fact that profitable levels for nitrogen applications vary greatly with the climatic conditions in which the crop is growing ; in sugar cane, excess nitrogen may lead to serious decreases in sugar yield. This has led to a search for an index of assimilatory activity or carbohydrate accumulation, so that the balance between carbohydrate and nitrogen reserves in the plant may be estimated. Clements (1940 ; Clements and Kubota, 1943) suggested that for sugar cane the sugar content of the young leaf sheaths would provide such an index (the " primary index "), while Nightingale (1942) for pineapple used an estimate of leaf colour. Both also analysed samples of selected tissue for the three principal nutrients ; Clements chose the leaf

blades of sugar cane for nitrogen determinations (Clements and Moriguchi, 1942), but preferred the young sheaths for estimating the potassium and phosphorus status of the plant. Nightingale (1942, 1942a) chose the meristematic tissue at the base of the leaves for analysis for all three nutrient elements ; only the nitrate fraction of the nitrogen present was, however, determined. The concentrations of nutrients to be desired in the index tissue varied with the stage of development reached. Both Clements and Nightingale have given examples of the practical use of the nutritional indices they propose for the purpose of controlling the application of fertilizers during the development of the crop, and, with the pineapple, anyway, this control is shewn to lead to more economical use of fertilizer. Nightingale's method has been used by Tam and Clark (1943) to follow the course of nitrification in sterilized soil. Borden (1942, 1944) too investigated the use of analysis for determining the nitrogen requirements of sugar cane ; among other techniques he tested that of Clements but did not find his " primary index" satisfactory. The total percentage of nitrogen in the whole plant, in the crusher juice and in leaf punch samples did however provide useful indices of nitrogen status ; but Borden emphasized the need for caution in applying his results to the practical control of nitrogen nutrition in the field.

**Determination of Soil Nutrient Status.**

The last group of investigations which we propose to include in this general survey of the use of plant analysis for diagnostic purposes consists of those whose primary intention was the description of *soil* conditions as affecting the plant, and not directly the nutritional status of the plant analysed. The results of such work have been considered to have general relevance to the nutritional status of crops grown on that soil. In many cases, such investigations led up to the survey of a wide range of soils to ascertain the distribution of different levels of nutrition among them.

Some of the work in this field does not even involve any interest in plant nutrition. Remington *et al.* (1929), for instance, have used the iodine content of the potato tuber as an index of the distribution of iodine levels for human nutrition. The selenium content of certain wild plants, notably *Astragalus* spp., has been used to survey parts of the United States for the probability of selenium poisoning of man and domestic animals (Byers *et al.*, 1938 ; Olson *et al.*, 1942, 1942a) ; and plant analysis has been widely used to judge the probable incidence of cobalt deficiency (McNaught, 1938 ; Beeson and Smith, 1944) in cattle. In some of the work on the heathlands of Northern Europe in which plant analysis has been used in surveys for copper, the main interest has been in animal nutrition (Sjollema, 1933 ; Beck, 1941), for a low copper content in the diet can lead to serious diseases of sheep (enzootic ataxia, " swayback ") and cattle (" *Lecksucht*," " falling disease.") Finally we may mention in passing Robinson's (1943) suggestion that analyses of hickory leaves could be used to indicate the abundance of the rare earth metals in the soil.

Let us turn now to those investigations in which information on soil composition was sought mainly on account of its relation to plant nutrition in general. As we have seen, many of the early investigators of the diagnostic use of plant analysis approached the problem from this point of view; but the most important recent work on these lines is that of Lundegårdh (1941), who in his method of " triple analysis" attained a much greater measure of success than any of the earlier workers, while concerning himself principally with the same crop plant—oats—as had been used in many of their investigations. The sample for analysis consisted of all the leaves, was gathered between panicle emergence and flowering, and was analysed for the three principal nutrients. From a very extensive series of field trials covering a large part of Sweden, it was possible to draw curves connecting the nutrient content of the sample with the response obtained to fertilizers ; these curves would subsequently enable the probable response on a soil of unknown characteristics to be estimated from analysis of a sample of oat leaves. It was a feature of this work that full account was taken of the interactions among the principal nutrients so that the estimated response to a potassium-containing fertilizer, for instance, was not based solely on the potassium content but was modified according to the phosphorus content found in the leaves.

For many years in Hawaii, analyses of sugar cane crusher juice have been carried out as a supplement to soil analyses (Moir, 1935 ; Borden, 1936b), for the purpose not only of characteriz-

ing the supply of plant nutrients from the soils of different fields, but also for assisting the interpretation of fertilizer trials and, on occasion, to show what treatments may be needed to improve the current nutrition of the crop. Among other investigations on these lines in relation to the principal nutrients for field crops may be mentioned that of Pierre and Pohlman (1933) on the exuded sap of maize and other Gramineae, and those of Gardner and Robertson (1935), Ulrich (1944) and Brown (1943) on sugar beet petioles. The Purdue University testing methods (see p. 71) have been used for soil survey purposes (Veale, 1942), as also have the tests in current use at Long Ashton Research Station (Jones and Russell, 1945 ; Plant, 1945, 1945a, 1945b).

Following observations (Teakle, Morgan and Turton, 1941 ; Teakle, Thomas and Turton, 1941) on the copper content of a number of crop plants in copper-deficient regions, Teakle (Teakle, 1942 ; Teakle and Turton, 1943) took a large series of samples of clover and cereal leaves from different parts of Western Australia, and analysed them with a view to determining the distribution of areas deficient in the trace elements copper, zinc and manganese. The clover samples were taken in the middle of the flowering period, those of oats at a height of 6-8 ins. Both plants were regarded as suitable for indicating copper and probably zinc requirements ; it was uncertain whether they were suitable for manganese, since manganese did not seem to be deficient in any part of the area covered. For clover samples, characteristic content figures for different levels of copper and zinc deficiency were suggested (Tables XI and XII).

Following a series of fertilizer trials on forest trees (Mitchell 1935, 1939 ; Mitchell and Finn, 1935 ; Mitchell and Chandler, 1939) Mitchell and Chandler were able to develop leaf analysis as a method for surveying the nutrient status of forest soils, particularly in relation to nitrogen. The leaf samples were taken in early autumn. It was claimed that this method of evaluation of the nitrogen-supplying power of the soil was not affected by rainfall, the physical properties of the soil, the age of the trees, or the local climate ; root competition had an effect, however, and a correction factor was proposed. For a number of tree species, limiting values for leaf nitrogen were determined (see Table XII) ; at localities where the leaf nitrogen content fell below this limiting value, the species could not be expected to succeed in competition with others. These methods were also used to study the nutrition of trees growing under experimental conditions (Finn, 1942, 1942a ; Finn and Tryon, 1942). Robinson and Edgington (1942) also suggested that analysis of the leaves of a forest tree—hickory—should be used to indicate the boron status of the soil on which it was growing.

There have been a number of instances in which samples from deciduous fruit trees have been analysed as a means of survey. Following the discovery that corky-core of the apple was a boron-deficiency disorder, a considerable number of analyses of apple fruits from different parts of New Zealand (N.Z. Dep. sci. industr. Res., 1937 ; Askew and Thomson, 1939) and Australia (Piper, 1936) were analysed for boron with a view to determining whether there were areas in which, although corky-core was at the time unknown, there was a risk of it developing in an unfavourable season. Batjer and Magness (1939) in Maryland made a survey of the potassium content of the leaves in a number of apple orchards, having found in sand culture experiments that maximum growth of the trees was not obtained unless the potassium supply was sufficient to maintain a potassium content of 1.7% in the leaves. The following year a similar survey of peach orchards was carried out (Cullinan and Waugh, 1940). Lilleland and Brown (1941, 1942) in California also surveyed peach orchards for potassium and phosphorus status by analysis of leaves collected in June and July—the period of greatest constancy of composition. Boynton and his collaborators (Boynton and Cain, 1942 ; Burrell and Boynton, 1943 ; Boynton *et al.*, 1944) used leaf analysis in a survey of the nutritional status of apple orchards in the State of New York.

This concludes the account of the main lines of development of diagnostic plant analysis during the last two decades ; that many investigations have been omitted or mentioned only inadequately stands to reason—particular points will be discussed in greater detail in subsequent pages.

# THE AIM OF A METHOD OF DEFICIENCY DIAGNOSIS

Before discussing the use of plant analysis for the diagnosis of nutritional deficiencies, it is advisable to attempt a definition of deficiency. From one point of view plant analysis could be regarded as a direct measure of deficiency, for when the nutrient content of the plant is low, the plant is obviously, in a sense, *deficient* in that nutrient. But deficiency is more often considered as involving sub-optimal development of the plant in some respect. Sub-optimal development is not, of course, necessarily ascribable to a nutrient deficiency, and consequently some further criterion has to be sought. The only satisfactory criterion would appear to be response to increased uptake of the deficient nutrient by an improvement in development. Cases have been known, however, where, although a particular nutrient is deficient, increase in its uptake has led to no improvement in development ; this may happen in certain types of chlorosis, where the iron is immobilized in the conducting tissue and increased supplies to the roots do not reach the leaves ; but such plants will usually respond to direct applications of iron-containing solutions to the leaf surfaces. Another group of doubtful cases which has to be covered by a definition of deficiency is that in which the nutrient applied, though its uptake is increased, does not act directly but by affecting the uptake of other nutrients or by altering growth conditions in some other way ; this includes most effects of lime and of sulphur applications to soils. It must therefore be stipulated that cure of the deficiency is a specific function of the deficient element. For the purpose of the present discussion, the following definition will be adopted, since it is brought into relation with practical needs :—

A plant is deficient in a certain element if supplying that element to the plant in a suitable form causes an increase in the yield, this effect being specific to the element in question.

A qualitative diagnosis of deficiency—i.e., a conclusion that the yield of a particular crop will probably be increased by fertilizer treatment—is in practice hardly adequate. What is required by the practical farmer of any method for determining fertilizer requirements is a forecast of the increase in the selling value of the total final product which may be expected as a result of any one of the whole indefinite range of possible fertilizer treatments. This selling value will depend not only upon the weight of whatever part of the plant is gathered for sale, but also on any quality criteria which may be in use.* If such forecasts are available, the farmer is then in a position to compute what treatment, at current fertilizer prices and costs of applying the material, will be likely to give the best return ; the forecast and the expected return will inevitably be subject to a measure of uncertainty unless and until weather conditions can be accurately predicted for the whole growing period of the crop, and pests and diseases can be brought under full control. Let us then bear in mind that the provision of such forecasts is the central purpose for which we are studying the potentialities of plant analysis ; let us also remember that, in order to be of practical use, a plant analysis technique must not only be able to give such estimates, but they also must be better estimates (that is, deviate less from the observed increase) than those from any other available technique for determining fertilizer requirements.

There is an important distinction among methods for the diagnostic use of plant analysis to determine fertilizer requirements which cannot be kept too clearly in mind. A hint of this distinction has already been introduced into the preceding section, but since it has rarely been recognized it is worth repeating more clearly :—

(1) Many techniques are directed to improving the nutrition, during the course of its later growth, of the crop plant analysed. Though results may affect the fertilizer treatment of subsequent crops, such an application of them is purely incidental.

(2) In other techniques the plants analysed serve only as an index of the state of the soil. There is no thought of remedying any state of unsatisfactory nutrition found in these plants—indeed, it would often be too late to do so—but it is intended to apply the results to improving the fertilizer regime for subsequent crops.

* For fodder crops consumed on the farm, the same considerations of quantity and quality apply.

# THEORETICAL

From the statement in the preceding section on the aims of a diagnostic method, it will be apparent that two major relations are involved :

(1) The relation of supply of nutrient to yield.

(2) The relation of supply of nutrient to its concentration in the tissues of the plant.

Each of these aspects covers a complex situation, and would demand a comprehensive discussion, but only certain general principles, in so far as they can be stated, will be considered.

## RELATION OF YIELD TO NUTRIENT SUPPLY AND UPTAKE

Two major considerations are concerned here : first, the supply of the nutrient from the rooting medium ; second, the utilization of the element after absorption by the roots. In the first problem are included all the questions of absorption, availability of the element in the soil, the effects of acidity, aeration, and so on. To avoid confusing the main issue such consideration will be left out of account. The second opens up the whole question of the physiology of growth. Only a few simple ideas need however be adumbrated. The utilization of the elements absorbed for growth will evidently depend upon the type of plant considered—whether it is perennial, biennial or annual in habit, whether of unlimited growth or strictly limited in size, whether or not of branching habit. As examples of these types we may cite the fruit tree as a perennial type with branched habit and unlimited growth ; the root crops as biennials with unbranched and determinate growth ; and the cereals as branched and determinate annuals. Other types not falling into these categories, such as the potato and tomato, might also be mentioned. Whatever the type of plant, however, the expansion of the growing system will depend upon the number, location and activity of the meristems or growing points. At germination all plants have only two meristematic regions, at the root and shoot apices, and all development depends upon the continued activity of these, and upon the laying down of secondary points of growth. This activity is conditioned by two sets of factors : (1) the external factors such as light, temperature, water supply and nutrient supply among others, and (2) internal factors, mainly nutritive but including hormones. Although of the external factors only nutrient supply is of immediate relevance, it should be stressed that the rate of laying down of new meristems, as well as of their development, is largely a matter of temperature level and is also affected by other external factors such as light.

With regard to the ' intensity ' level of all these factors, the following generalisation is possible, namely, that for each factor in turn there is an optimum level and that growth is increased if the intensity is brought to this level and decreased if it is raised further. These optima are not fixed, but depend upon all factors simultaneously ; nevertheless in theory one may postulate an optimal concatenation of factors at which development of the plant would be maximal, and that no greater rate could be attained by alteration in the level of any one or more factors. The maximal yield of the plant would then be secured, and would be determined entirely by internal genetic factors.

Assuming then that all external factors including all nutrients except one are maintained at optimal level, then as this is raised growth made will be a function solely of the available amount of this single nutrient, and as the optimum is approached the " maximum possible yield " of the plant will be reached. What will now be the relation of yield to the amount of nutrient available ? Two answers have been proposed : (1) the law of limiting factors originally due to von Liebig (1863) ; and (2) the law of diminishing returns, as exemplified by the views of Mitscherlich (1909). According to the first a linear relation between the yield and the amount of nutrient given is expected,* while the second leads to a curve resembling a hyperbola in form,

* von Liebig's formulation was in very general terms : " Every field contains a *maximum* of one or several, and a *minimum* of one or several, other nutritive substances. It is by the *minimum* that the crops are governed." (*loc. cit.*, p. 213). This does not appear to imply any particular form of the rising limb of the curve connecting yield with nutrient supply, but that Liebig did envisage it as linear is shown by the following quotation : " If we wished, by increasing the phosphoric acid required for the formation of seed, to enable a wheat field yielding an average produce of six grains to give two additional grains, it would be necessary to increase by ⅓rd the whole amount of the phosphoric acid present in the field, and serving for the formation of seed." (*loc. cit.*, p. 126).

with maximum gradient at low nutrient levels and approaching a maximum value. Where the increase of a single nutrient factor in the presence of excess of the others is concerned both field and pot culture experiments confirm this diminishing returns relation. The exact mathematical formulation by Mitscherlich is of no ultimate importance except as a method of interpolation. For each series of increasing doses of a nutrient a " maximum possible yield " is assumed, which will depend upon all the other factors operating ; in practice, approximation to this is established by experiment and holds for the particular experiment only. In the field (without such manurial trials) the maximum possible yield is not known and cannot be predicted. If a diminishing returns relation holds (such as Mitscherlich has assumed), the hope of attaching to each nutrient a specific numerical value stating the increase in yield for each unit of nutrient applied (cwt. per acre or other convenient measure) must be abandoned, since the return will depend upon the level of the nutrient already present. In place of this, on Mitscherlich's formulation of yield relations a value (" *Wirkungsmenge* ") can be stated for the amount of any nutrient necessary to bring the yield to any fraction of the " maximum possible yield". If Mitscherlich is correct in his assumption, these values will be independent of the maximum possible yield, and specific for the nutrient element.

The Mitscherlich relation in its simplest form, then, presupposes the presence in excess of all nutrients except the one " limiting " growth. If two elements are simultaneously increased in constant proportions, the combined effect will be the *product* of the individual effects (Baule, 1918) and the curve relating yield to dosage given becomes sigmoid, the precise form varying according to the relative proportions supplied.

The effects on yield of the simultaneous variation in the supply of more than one nutrient have been represented mathematically in a different way by Maskell and by Balmukand (1928). This has become known as the " Resistance Formula," and presupposes that the reciprocal of the yield is the sum of various terms each proportional to the reciprocal of the quantity of a single nutrient supplied. This formulation has been shewn to apply in practice more successfully than that of Mitscherlich.

The work of Gregory (1937) has shewn that under certain circumstances the relation of yield to simultaneous increase in dosage of two nutrients in constant proportions is represented by a straight line. These results were obtained with nitrogen, phosphorus and potassium manuring of barley. By plotting the yield obtained against the amount of nutrient taken up by the plant, three types of relationship were established : (a) With excess of all nutrients except one, which is given in increasing doses, the relationship of yield to the uptake of the nutrient in minimum is given by a curve of the diminishing returns type ; (b) When yield is plotted against the uptake of one of the nutrients *not in minimum*, a curve of yield rising throughout is obtained ; (c) when the supply of two nutrients increased in a certain fixed proportion, the curve relating yield to the uptake of either nutrient became linear, as indicated above. It was further shewn that in sand culture over a wide range the rate of uptake by the plant of the nutrient in minimum was proportional to the amount of nutrient applied to the sand, so that, for the first approximation, the conclusions derived from the amounts taken up can be extended to the amounts of nutrient available to the plant. It should be noted that in these experiments the nutrient doses were added to the sand at germination, so that the concentration in the medium was falling throughout, and most of the nutrient was absorbed in the stage of early growth prior to flowering. With plants growing in soil these relations are necessarily modified, for supply is continuous, although in annuals such as cereals the plant develops under conditions of falling external concentration.

The bearing of these findings on the main problem of deficiency is very evident. Under certain conditions, namely a certain unique proportion of two nutrients, with increasing dosage the increment in yield is directly proportional to the supply, and an estimate of yield will give direct information as to the amounts of the nutrients in the soil ; only under the particular condition of *balance* of the nutrients, or where one is known to be in minimum, can an estimate of total uptake by the whole plant be a measure of the status of a particular nutrient in the soil. In practice, this precondition presupposes a knowledge of conditions in the soil which is exactly the information which a diagnostic method is expected to provide. This leads directly to the second aspect of the problem.

## RELATION OF INTERNAL NUTRIENT CONCENTRATION TO NUTRIENT SUPPLY

A divergence of the discussion is necessary here. It has already been pointed out that the development of the plant is determined by the activity of the meristems, and the laying down of secondary growing points. Now the various nutritive elements differ greatly in their effects in this respect. Without going deeply into the question, it may be stated that these effects all depend upon the part played in metabolism, particularly in protein synthesis, since all cell division depends primarily upon cytoplasmic and nuclear proliferation. As might be expected, then, nitrogen plays the chief part, followed by phosphorus and potassium, to name only the three major nutritive elements.

With a nutrient supply in which all elements except one are maintained at high level, the concentration within the plant of the nutrient in minimum will rise with increasing external supply. In general, the concentration of the element in the plant will depend upon the specific relation of the nutrient to the growth process, the rate of uptake, and the rate of utilization. Thus, with nitrogen deficiency growth remains low, no auxiliary meristems are laid down, but the uptake of other elements such as phosphorus and potassium does not cease and these are therefore present in relatively high concentration in the tissues. The same is true to a less extent with phosphorus deficiency, whereas with potassium deficiency growth does not cease and so the nitrogen concentration does not rise to the same degree. The point to be stressed is that the relative concentration of the nutrient elements in the tissues is no measure of the level of supply of any particular element, but depends upon the total supply of all elements—to a varying degree according to the importance of a particular element in the metabolic processes. In a balanced system of nutrients, at any particular stage of growth the relative concentrations may remain unchanged although the size of the plant, and hence the yield also, rises with increasing dosage of the nutrients. The development of deficiency symptoms, too, gives information as to the relative and not the absolute levels of the nutrient factors.

When development of the plant is depressed by low level of external factors such as water supply or temperature, internal concentration will rise ; this is true also when slow development is due to lack of any one of the nutrient elements. This simple relationship elucidates the question of " luxury consumption ", and the three types of relation between yield and nutrient supply discussed above.

In considering the changes in internal nutrient concentration through the growing season, the type of plant is of importance. The considerations of yield relations dealt with above relate to the state of affairs at the end of the growing season. This in the case of annual plants only will correspond with the final harvest yield ; with biennial and perennial plants the growth cycle will be incomplete and the relations somewhat different. For the sake of simplicity an annual plant, such as a cereal, will be considered.

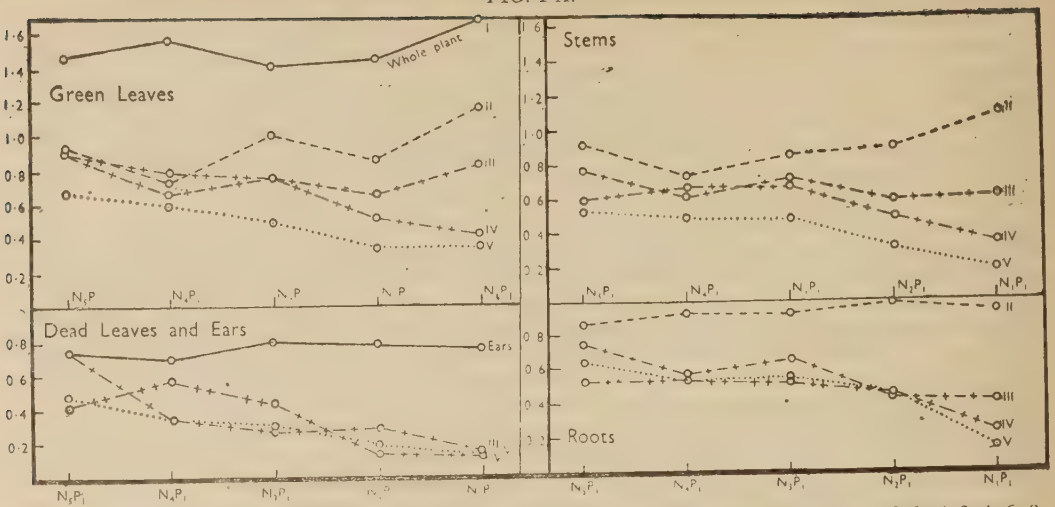
To bring out as clearly as possible the relations of nutrient supply to internal concentration, some data on the growth of barley obtained by Gregory are presented in some detail. The experiment concerned the interaction of nitrogen and phosphorus, was carried out in sand culture, and was designed on a factorial basis. Five levels of deficiency for each nutrient were used, each member of a series receiving one-third that of the preceding. Thus the range of concentrations for nitrogen were as follows (per pot of three plants) : $N_1$, 1215 mg. ; $N_2$, 405 mg. ; $N_3$, 135 mg. ; $N_4$, 45 mg. ; $N_5$, 15 mg. For $P_2O_5$ one-third of these amounts was given. The suffixes therefore correspond with increasing deficiencies of nutrient. In every case, the total nutrients were added in solution before germination.

The complete interaction experiment may be represented as follows :—

| | | | | |
|---|---|---|---|---|
| $N_1P_1$ (1 : 1) | $N_1P_2$ (1 : 1/3) | $N_1P_3$ (1 : 1/9) | $N_1P_4$ (1 : 1/27) | $N_1P_5$ (1 : 1/81) |
| $N_2P_1$ (1/3 : 1) | $N_2P_2$ (1/3 : 1/3) | $N_2P_3$ | $N_2P_4$ | $N_2P_5$ |
| $N_3P_1$ (1/9 : 1) | $N_3P_2$ | $N_3P_3$ (1/9 : 1/9) | $N_3P_4$ | $N_3P_5$ |
| $N_4P_1$ (1/27 : 1) | $N_4P_2$ | $N_4P_3$ | $N_4P_4$ (1/27 : 1/27) | $N_4P_5$ |
| $N_5P_1$ (1/81 : 1) | $N_5P_2$ | $N_5P_3$ | $N_5P_4$ | $N_5P_5$ (1/81 : 1/81) |

Each edge of a square, defined by $N_1P_1$, $N_1P_5$, $N_5P_5$, and $N_5P_1$, as the corners, would represent a series of increasing concentration of one nutrient (limiting series), all other nutrients being present at constant level. A diagonal would represent a simultaneous increase in both nutrients (balanced series). The numerals in parenthesis (shewn above) represent the relative proportions of the nutrients in terms of the standard amounts given.

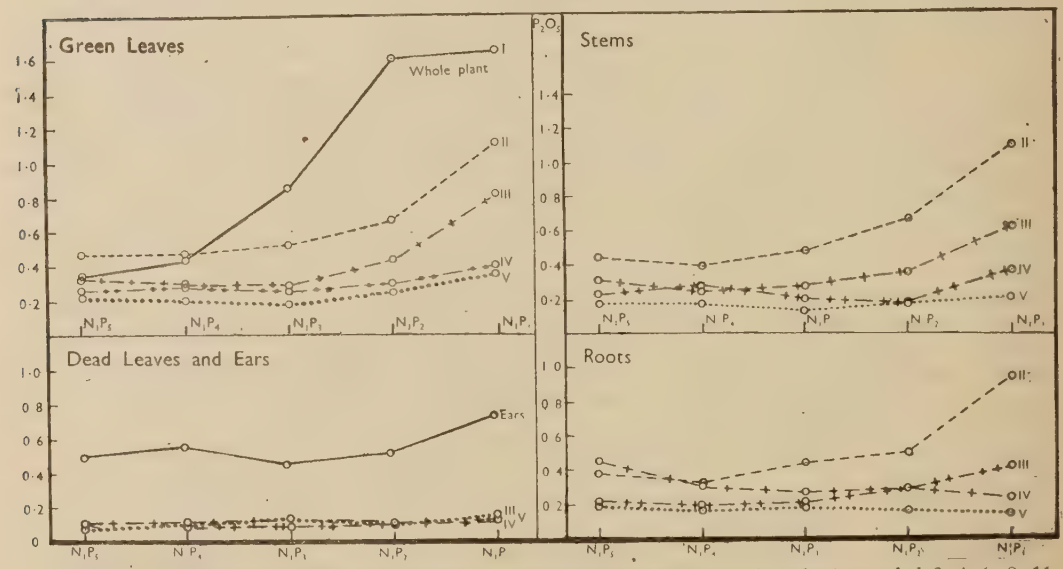
FIG. 1 A.




Phosphorus content ($P_2O_5$% in dry matter) of various organs of the barley plant sampled at 2, 4, 6, 8, 11 weeks (I—V) from germination.

$N_5$ → $N_1$ increasing N supply (5 → 405 mg. N per plant).
$P_1$ maximum P throughout (135 mg. $P_2O_5$ per plant).
Nitrogen in minimum, phosphorus in excess.

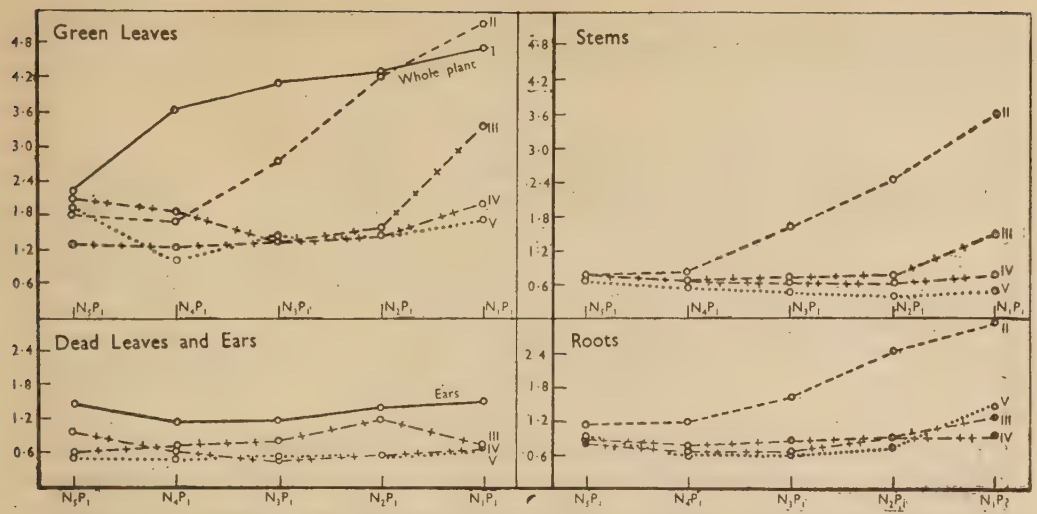
FIG. 2 A.




Phosphorus content ($P_2O_5$% in dry matter) of various organs of the barley plant sampled 2, 4, 6, 8, 11 weeks (I—V) from germination.

$N_1$ maximum N throughout (405 mg. N per plant).
$P_5$ → $P_1$ increasing P supply (1.7 → 135 mg. $P_2O_5$ per plant).
Nitrogen in excess, phosphorus in minimum.

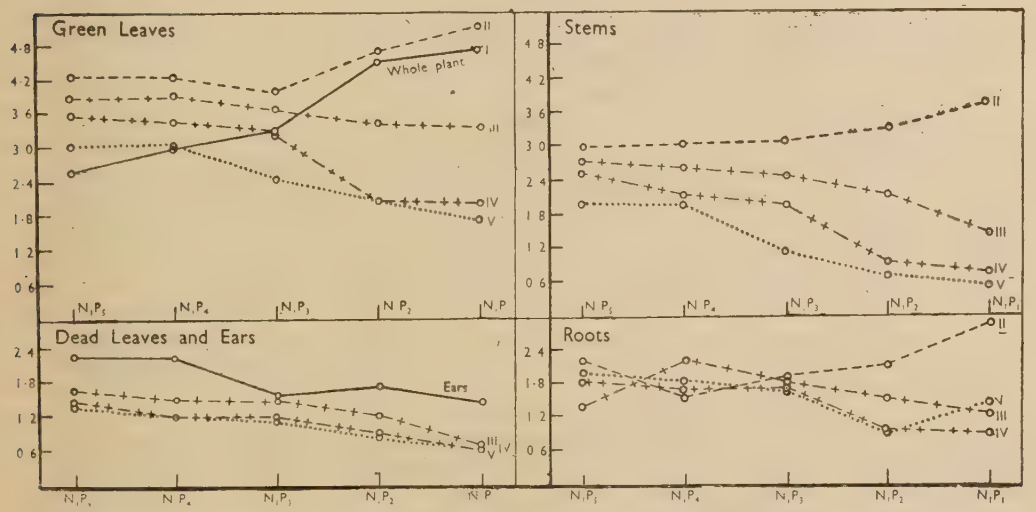
FIG. 1 B.




Nitrogen content (N% in dry matter) of various organs of same plants at same sampling times as those in Fig. 1A.

$N_5 \rightarrow N_1$ increasing N supply (5 → 405 mg. N per plant).
$P_1$ maximum P throughout (135 mg. $P_2O_5$ per plant).
Nitrogen in minimum, phosphorus in excess.

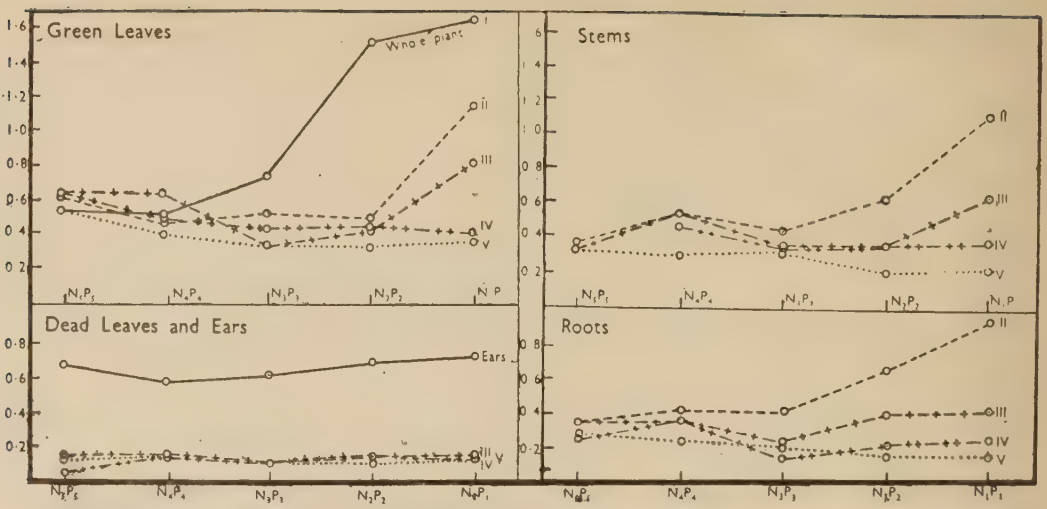
FIG. 2 B.




Nitrogen content (N% in dry matter) of various organs of same plants at same sampling times as those in Fig. 2A.

$N_1$ maximum N throughout (405 mg. N per plant).
$P_5 \rightarrow P_1$ increasing P supply (1.7 → 135 mg. $P_2O_5$ per plant).
Nitrogen in excess, phosphorus in minimum.

FIG. 3 A.




Phosphorus content ($P_2O_5$% in dry matter) of various organs of the barley plant sampled at 2, 4, 6, 8, 11 weeks (I—V) from germination.

$N_5 \rightarrow N_1$ increasing N supply (5 → 405 mg. N per plant).
$P_5 \rightarrow P_1$ increasing P supply (1.7 → 135 mg. $P_2O_5$ per plant).
Nitrogen and phosphorus balanced.

The variation in yield obtained in this series of cultures is shewn in Table III. The yields are given in gm. dry matter of grain per pot of 3 plants, and expressed on an acre basis would correspond to an extreme range of 1.0 — 47.5 cwt.

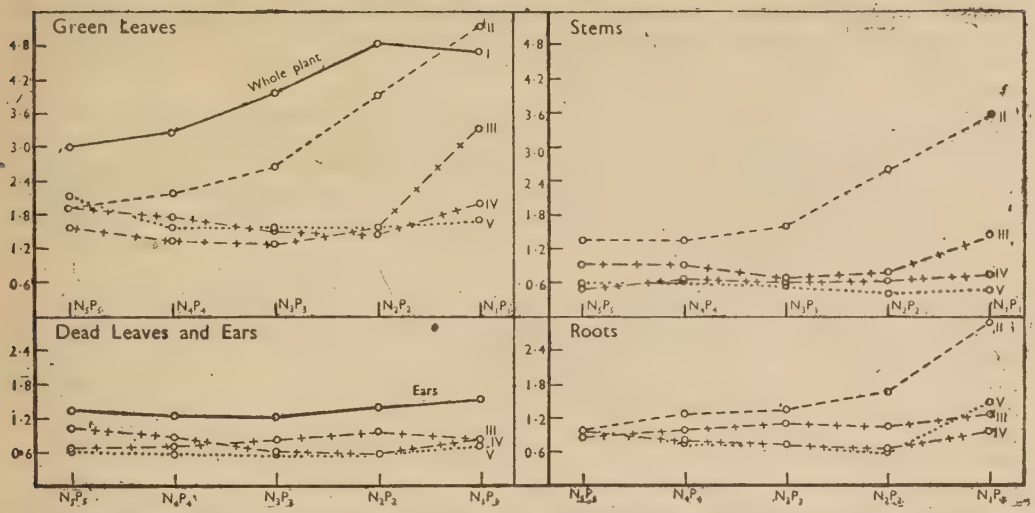
**Table III**

**Yields of barley plants under varying nitrogen and phosphorus nutrition (gm. per pot of grain, dried at 100°C.)**

| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ |
|---|---|---|---|---|---|
| $N_1$ | 33.0 | 18.9 | 2.70 | 1.32 | 0.70 |
| $N_2$ | 10.54 | 10.86 | 4.94 | 3.59 | 2.45 |
| $N_3$ | 4.64 | 4.43 | 4.20 | 3.50 | 3.47 |
| $N_4$ | 1.98 | 1.94 | 2.20 | 1.97 | 1.27 |
| $N_5$ | 1.20 | 1.22 | 1.04 | 1.20 | 1.00 |

The internal concentration of nutrients for the series with phosphorus at high level and increasing doses of nitrogen are given in Fig. 1, those with nitrogen at high level and increasing doses of phosphorus are shewn in Fig. 2, while the data in Fig. 3 refer to the "balanced" series.

FIG. 3 B.




Nitrogen content (N% in dry matter) of various organs of same plants at same sampling times as those in Fig. 3A.

$N_5 \rightarrow N_1$ increasing N supply (5 → 405 mg. N per plant).
$P_5 \rightarrow P_1$ increasing P supply (1.7 → 135 mg. $P_2O_5$ per plant).
Nitrogen and phosphorus balanced.

For each of these series, two diagrams are given, A representing the percentage of $P_2O_5$ in the tissues and B the percentage of nitrogen. It should be emphasized that the analyses in Figs. A and B relate to the same set of plants, so that the relative internal concentrations of nitrogen and phosphorus for each manurial combination can be ascertained. Furthermore, the concentrations in various organs of the plant are presented, namely green leaves, dead leaves, stems, roots and ears. The plants were sampled on five occasions during growth, viz. 2, 4, 6, 8 and 11 weeks from germination. The curves referring to these sampling occasions are numbered in Roman numerals (I—V). On the first sampling occasion the organs were not separated, and the curves for the whole plant at this time are entered with those for the green leaves, which at this time formed the bulk of the material. The data for the ears are entered with those for the dead leaves; for the latter only three curves are given, since before the sixth week very few dead leaves were present.

The rate of uptake of the nutrients immediately after germination will depend upon the concentration of the nutrient at the root surface. In consequence of the uptake, growth will proceed, and, if the nutrient is primary and determines meristematic activity, as in the case of nitrogen or phosphorus, the rate of laying down of new meristems and differentiation of primary meristems will be determined by the internal concentration. But it must be realized that the position of the new meristems is determined by the structure of the plant. Thus, in the cereal a new branch (tiller) is laid down in the axil of every early leaf; as development goes on new possible positions of branches appear, and the whole system tends to extend exponentially. The rate of development is, however, circumscribed and controlled by the external factors of light, temperature, water and so on. If these are present at optimal level, development will reach its maximum possible value. Not only does the shoot of the plant develop in this way, but the root system also, and as the total uptake depends on the extent of the root surface the uptake will also tend to increase exponentially (with increasing velocity). The concentration of the

nutrient in the soil solution is the other factor concerned in total uptake,* and as this tends to be high in spring uptake in the early stages of growth will be high for this reason and tend to fall as the nutrients are exhausted. Other factors, themselves determined by the balance of nutrients, are concerned—namely the relations of growth of root and shoot, which complicate the issue but do not fundamentally change the picture.

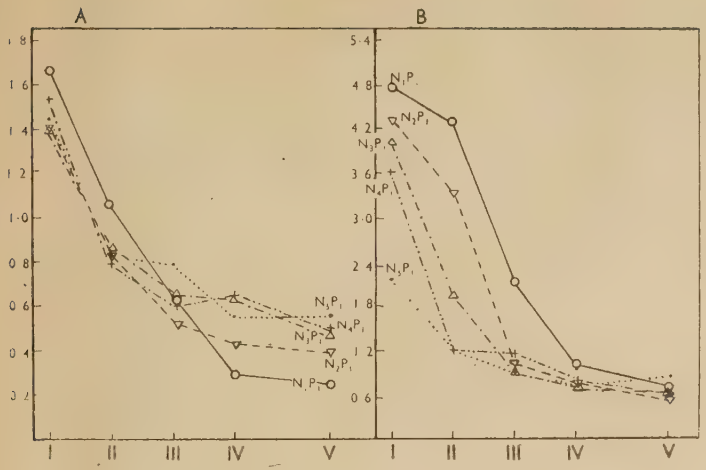
In the early stages of growth, then, concentration of the nutrients will be high since the supply is high and demands are then low owing to the few growing points present at that time. In the interaction experiment already described, high concentration at first was secured by addition of the total nutrient dose before germination. The variation of the external concentration is reflected in the whole plant analyses, sample I. In Fig. 1B, nitrogen concentration rises with increasing nitrogen supply, and in Fig. 2A a similar result is seen for phosphorus where phosphorus doses increase. Comparing Figs. 1A and 1B, it is seen that, so far as phosphorus content is concerned, where phosphorus level is the same throughout the series the internal concentration in the plants remains high and nearly constant. In Fig. 2B, as contrasted with Fig. 2A, the internal nitrogen concentration, although at a constant level of supply, shews a rise as the phosphorus level is increased. This may perhaps be accounted for by the fact that the nitrogen content of the roots is always lower than that of the green portions, and with low external concentration of phosphorus the roots form a relatively high proportion of the plant. Since sample I consists of the whole plant, the proportion represented by roots decreases as the level of phosphorus is raised, and hence the percentage content of nitrogen tends to rise. In the case of phosphorus, the percentage content of the roots is similar to that in the aerial portions, and consequently the concentration of phosphorus in the whole plant (Fig. 1A) is uniform throughout the series. By the time of the second sample this effect is no longer apparent, and in Fig. 2B all organs of the plant at this stage display only small differences in nitrogen content with increasing phosphorus supply.

The changes in concentration in the various organs during the growth cycle are clearly shewn in all the diagrams. In leaves, stems and roots the concentration of the nutrient in minimum falls, so that by harvest the internal concentration of the nutrient in minimum is always low and almost independent of the original external supply. This can be seen for nitrogen in Fig. 1B and for phosphorus in Fig. 2A. It should be noted that this low content independent of supply is seen in the dead leaves as early as the third sample, which is a consequence of the mobilization of the nutrient from the senescent leaves to supply the meristems. The changes in internal concentration during development are the greater, the higher the original level of supply of the nutrient " limiting " growth—best seen in the stem data in Fig. 1B, and those for leaves and stems in Fig. 2A. The relation of external supply to internal concentration of the other nutrient, always at high level, is in marked contrast, as seen in Figs. 1A and 2B, in the following respects. At the time of the second sample, in all organs the internal concentration is almost unaffected by the supply of the other nutrient, and as sampling progresses the internal concentration of the nutrient at high level falls more and more, the greater the supply of the "limiting" nutrient. This is well shewn in all organs of the plant, and is a result of the greater growth made with increasing supply of the nutrient in minimum. In consequence, at harvest the concentration of the element in relatively high supply remains high. The same relations are seen in the dead leaves, indicating that the nutrient in abundant supply is not mobilized from the senescent portions. This is the principal meaning of "luxury consumption." Where the nutrients have been supplied in balanced proportions, these effects of " luxury consumption " are not seen. Figs. 3A and 3B shew that the behaviour with regard to internal concentration of both nitrogen and phosphorus is very similar, and resembles that already found for the nutrient " limiting" growth in the other two diagrams.

The combined effects of the changing concentrations in the organs during development are shewn in Figs. 4—6, where the internal concentrations in the whole plant of nitrogen and phosphorus are presented at the various sampling occasions. As in the separate organs, the concentration of the nutrient in minimum displays large differences in the earlier samples, but the curves converge to a low level by harvest (see Fig. 4B for nitrogen and Fig. 5A for phosphorus).

* Actually the nutrient concentration within the conducting tissues of the root is also involved, since the rate of uptake depends upon the concentration gradient across the outer tissues of the root.

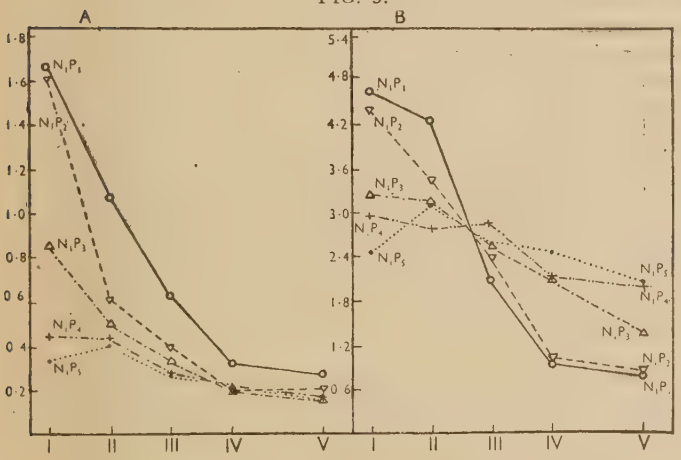
FIG. 4.




Drift of phosphorus (A) and nitrogen (B) (% content in dry matter) in whole barley plants sampled 2, 4, 6, 8, 11 weeks (I → V) from germination.

Nitrogen varying and phosphorus maximal.

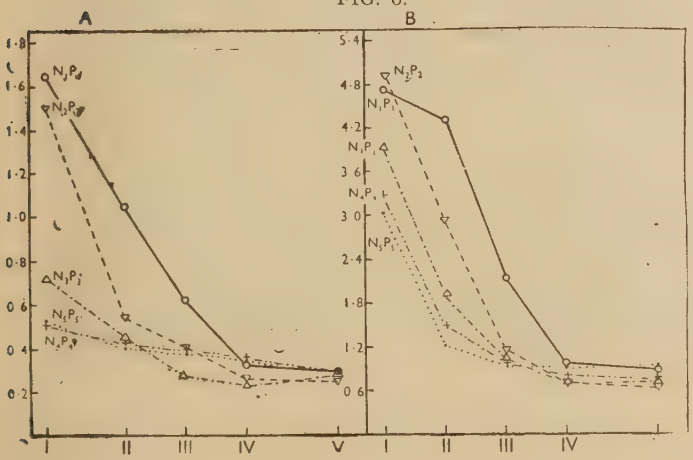
FIG. 5.




Drift of phosphorus (A) and nitrogen (B) (% content in dry matter) in whole barley plants sampled 2, 4, 6, 8, 11 weeks (I → V) from germination.

Nitrogen maximal and phosphorus varying.

FIG. 6.




Drift of phosphorus (A) and nitrogen (B) (% content in dry matter) in whole barley plants sampled 2, 4, 6, 8, 11 weeks (I → V) from germination.

Nitrogen and phosphorus varying together; balance of N : $P_2O_5$ constant at 3 : 1.

The relations for the nutrient in constant high supply are seen in Figs. 4A and 5B. In the former case the concentration of phosphorus varies little at the first sample, but large differences appear by harvest, at which time the series of increasing nitrogen supply appears as a series of falling internal phosphorus concentration. The same kind of relation, though much more marked, is seen for nitrogen in Fig. 5B, which represents the nitrogen concentration in plants with high constant nitrogen supply and increasing phosphorus. The order of nitrogen concentration undergoes a complete reversal between the first sample and harvest, and the curves intersect at a single point (some five weeks from germination) *at which time plants of very different size have uniform nitrogen concentration.* The curves in Fig. 6 refer to the " balanced " series, and these both resemble each other in general type and are similar to the corresponding curves for the element in minimum—thus, Fig. 6A resembles Fig. 5A, and Fig. 6B Fig. 4B. A similar kind of relation has also been shewn to hold for the interaction of nitrogen and potassium (Gregory, 1937, and Fig. 2).

The elucidation of the results just presented would require a lengthy discussion of the mode of growth and changes in growth rate of different organs throughout development in the different series. Some data bearing on these relations have been presented elsewhere (Gregory, 1937). Suffice it now to say that the continued development of each meristem is exponential, while at the same time new growing points develop, so that an ever-increasing demand is imposed upon supply for further growth ; eventually demand overtakes supply, and a condition of "internal starvation " supervenes. This is reflected in the increasing senescence of the organs first formed, and in mobilization and transfer of some nutrients thence to the parts still meristematic. The nutrients differ in this respect, for whereas, as has been indicated above, nitrogen, phosphorus and potassium readily become again available, this is untrue of calcium. Among the minor elements, boron is mobilized only to a slight extent (Cooper, 1937 ; Wolf, 1940).

These considerations bear on the problem under discussion in two ways : (1) the concentration in the tissues will depend upon the time during development at which determinations are made ; (2) the results will depend upon the part of the plant chosen. Analysis of the plant soon after germination (as soon as seed reserves are exhausted) will give some measure of the concentration of the nutrients in the rooting medium. The data for barley already dealt with shew this clearly, and with cotton Crowther (1941) has shewn that by analysis of the leaves within the first two months after germination the yield could be forecast with a high order of accuracy. It should not be supposed that the nutrient concentration at this stage of development will in all cases represent the maximum correlation with yield ; other types of plant which do not branch very rapidly in the early stages may not display the phenomenon of " internal starvation," which has been postulated for the cereal type of development—on which this high correlation with yield ultimately depends.

The rather lengthy discussion refers to plants grown under somewhat artificial conditions, and it is necessary to consider the bearing of the ascertained facts on the relations to be expected with plants growing in the field. The outstanding difference arises from the mode of supply of the nutrient, for, first, although in the field the concentration in the soil solution tends to be higher at germination than later in the season, the differences in concentration encountered are of quite a different order from those employed in the sand cultures described. Second, the nutrient supply to the soil solution is a continuous process, and the rates at which the nutrients become available are likely to be more important than the actual concentrations—indeed, under a crop the concentration in the soil solution may fall almost to zero, owing to the more rapid uptake by the plant than the rate of release from the soil particles. Third, in certain types of plant with large capacity for meristematic multiplication, such as barley, it is found that at a certain stage (in this case, flower differentiation) further elaboration of meristems ceases, and therefore nutrients taken up after this stage lead to no further increase in yield, but instead the nutrient absorbed raises the concentration within the plant and checks the normal tendency to decline to a minimum at harvest irrespective of the original supply level. It is therefore not surprising to find that plant analyses from field crops can display considerable variations in concentration at the stage of harvest. In dealing with the literature many examples have been cited of high concentrations of nutrient in the mature cereal plant ; this may be due to two different causes : first, the limitation of growth by some other nutrient factor leading to "luxury

consumption " ; second, a high supplying power of the soil maintained throughout the growing period. In the former case yield will tend to be low and could be improved by the addition of the nutrient in minimum ; in the latter case, yield will be high. The proposals to use analyses of mature cereal plants as indicators of the nutritional status of the soils on which they were grown thus depend upon the fact that differences in the nutrient-supplying power of the soil persist throughout the growing season, leading to accumulation in the later stages, and not upon any direct causal relationship between final internal nutrient concentration and yield. The utility of top dressings for increasing yield is entirely limited by these facts, for if supplied after the critical phase is past the nutrient supplied may have no effect on yield.

## RELATION OF YIELD TO INTERNAL NUTRIENT CONCENTRATION

The preceding discussion has dealt with the effects of varying nutrient supply on yield and on nutrient concentration within the plant. It is now necessary to pose the question of the relationship between the latter two quantities. It has been shewn that as the level of a nutrient not in ample supply is increased, other factors being held constant, both yield and internal nutrient concentration rise—at least in certain plant organs and at certain stages of development. Indeed, attempts have been made to express this relationship in a mathematical form ; Pfeiffer *et al.* (1919) proposed a hyperbolic formula, Gast (1937) found the yield of pine seedlings to be linearly related to the logarithm of the internal nitrogen concentration, while Mitchell (1939) found the relation between yield and internal nutrient concentration to be nearly linear until the maximum yield was reached. Macy (1936) distinguished three portions of the curve relating yield to internal concentration—the " minimum percentage" portion where yield rises, although internal concentration remains constant (presupposing a minimal concentration in the plant, c.f. Heinrich, 1882 ; von Dikow, 1891 ; Helmkampf, 1892) ; the " poverty adjustment" region, in which both yield and internal concentration increase ; and finally a " luxury consumption " region in which yield remains constant with rising internal concentration. The transition from the " poverty adjustment " to the " luxury consumption " region took place at the " critical percentage." These interpretations apply to a situation in which one nutrient only is varied, and presuppose that yield rises with increasing supply of this nutrient—i.e., that growth is "limited" by this nutrient. If however the conditions studied cover a wide range of combinations of nutrient factors, it is clear that the internal concentration of one alone of these nutrients is unlikely to be related to yield over the whole range. Such varying combinations are in fact found in the field, as is shewn by the varying manurial responses of plants in different soils.

A method for the diagnosis of fertilizer requirements is not directed primarily to forecasting the yield, but rather to forecasting the response of the plant to the addition of a nutritive element, so that by providing this after diagnosis yield may be improved. The minimal requirements to develop such a method would be data for plants growing in a series of substrates at various levels of one factor with the others in excess, including first the internal concentration of the varying nutrient at a definite stage in definite organs, and second the increase in yield resulting from the application of a definite quantity of the nutrient at this time. The increments in yield resulting from this specified addition of nutrient could then be represented graphically as a function of the nutrient concentration within the plant at the time of application. Such a graph would form the basis for forecasting the effect of the nutrient addition. Data of this kind have been presented by Crowther (1937), Craig (1940), Lundegårdh (1941) and Emmert (1942a). Lundegårdh claims that for a single nutrient the relationship can be expressed mathematically by an equation of the type

$$y = \frac{a}{x^c}$$

where y is the yield increment resulting from the addition of a specified amount of nutrient and x the concentration of this nutrient in the plant at flowering time, a and c being constants.

It is important, however, to consider the effect of the levels of other factors on the postulated relationship. It has been claimed by Pfeiffer *et al.* (1919) that this relationship, when expressed in terms of percentage increment in yield is independent of the supply of other nutrients and of environmental factors ; but relative yield increments are of no practical importance since the

absolute increase is not implied. Macy (1936) claimed that his "critical percentages" were largely independent of the level of the other "ordinary growth factors," while Chapman (1941) considered that in his data for rubber the relationship between growth and internal nutrient concentrations followed a law of limiting factors*—which would be in line with the suggestion frequently made (Wallace, 1928a; Thornton, 1932; McDonald, 1934; Thornton *et al.*, 1934; Scarseth, 1941, 1941a; Ulrich, 1944) that plant analysis will often shew only which nutrient is "limiting." It may be doubted, however, whether these claims could be maintained as generalisations in face of the evidence provided by Lundegårdh (1941) that the absolute increment in yield resulting from a given fertilizer application to plants with a particular internal concentration of the nutrient supplied in it is markedly affected by the level of other nutrients (Table VI); see also Emmert, 1942a). The yield increment as determined by more than one factor was considered by Lundegårdh to be represented by a general equation of the form

$$y = \frac{k}{x_1^{c_1} \cdot x_2^{c_2} \cdot x_3^{c_3}}$$

so that for many factors acting simultaneously the yield increment is proportional to the product of the effects of the single factors. The question as to whether this equation correctly represents the relationships is not a matter of immediate concern, and the evidence in support of it is far from conclusive.

In the method outlined above, the effect of the other factors on yield increment can be ascertained by analysing the plants for all the nutrient factors at the time of application. In this way, the yield increment can be represented in terms of combinations of concentrations, which for two factors could be portrayed in a solid diagram. For more than two factors the relationships could be represented algebraically by regression equations. At present no adequate data of this kind are available, though Lundegårdh's work indicates the direction in which progress can be made.

In spite of the view of Pfeiffer and his colleagues already quoted, it would be unwise to rule out the possibility that the relation between plant composition and increases in yield due to nutrient supply may be affected by differences in external factors such as light, temperature and water supply. Mitchell (1934), for instance, published results suggesting that light intensity affected these relationships in pine seedlings; work at Lichterfelde (Eckstein *et al.*, 1931) indicated that shading affected potassium relations in potatoes; and Nightingale (1942) found that the nitrate content in the pineapple corresponding to optimal nitrogen nutrition was higher when conditions favourable to assimilation led to a high starch content than when it was low.

## POSSIBLE DIFFICULTIES IN THE DIAGNOSTIC USE OF PLANT ANALYSIS

Before considering practical aspects of the proposals for the diagnostic use of plant analysis, it will be helpful to indicate conditions, which might be encountered in practice, under which such diagnostic methods must fail. The validity of the use of plant composition as a diagnostic index depends upon the assumption that to each set of concentration data there corresponds a unique potential response in yield to the application of each nutrient at that time or subsequently. If the same plant composition is associated with more than one potential yield response to fertilizer application, it is self-evident that analysis of the plant can provide no means of distinguishing between these diverse possibilities. That this does in fact hold, at least over certain ranges, has several times been suggested. The view has been ascribed to von Liebig, as a corollary to his "Law of the Minimum," that the composition of any plant species is constant (Thomas 1929, 1934), though in fact von Liebig (1863) seems to have limited himself to postulating that the proportion of the various ash constituents to one another is constant—and in some species at least he admitted the possibility of mutual replacement of bases (1840, 1863); Joulie (1876) has

* c.f. also the remark of Heinrich (1882), in regard to the composition of oat roots, "that that component which is present in smallest quantity decides the yield and determines whether the crop shall be light or moderate. The other nutrients may then be present in much greater amounts . . . . without causing any increase in the yield."

also been quoted (Lagatu and Maume, 1927) as considering that each species had a typical composition, from which only slight deviations occurred; but he continued by shewing how potassium deficiency in wheat could be diagnosed by the difference in composition of good and bad plants from the same field. In spite of the many tabular presentations of "typical" composition of plant organs, it is doubtful whether the view has ever been seriously held that the composition of any plant or organ is invariable.

A variant of this view ascribed to von Liebig lies in the possibility of minimal nutrient concentrations within the plant—that is, it has been suggested that if the supply of a nutrient is progressively reduced, the percentage of that nutrient in the plant diminishes only to a certain point, and then remains constant, although yield continues to decrease. As shewn in the previous section and in Table XII, several of the earlier workers attempted to determine such minima; whether this is in general a correct representation of the course of change of nutrient content with nutrient supply is, however, doubtful,—although, as has been shewn for cereals (Figs. 1—3), as growth proceeds the internal concentration tends to a constant minimal value irrespective of original supply. Under such conditions, it would follow that it would be impossible to distinguish by plant analysis between different levels of deficiency falling within this minimum zone. If a maximum nutrient content were reached at a nutrient supply level insufficient to give maximum yield, this would likewise reduce the value of plant analysis for diagnostic purposes; von Dikow (1891) and Helmkampf (1892) postulated such a maximal nutrient content, but seem to have envisaged it as being reached only at a nutrient supply level such that further additions cause no further increase in yield; a maximum of this type would be no disadvantage to the diagnostic use of plant analysis. Süchting (1939) found that in forest tree seedlings supplying a nutrient to plants severely deficient in it caused increases in both yield and the nutrient concentration within the plant, but that at less severe levels of deficiency increases in nutrient supply caused further increase in yield without any accompanying increase in internal concentration. It should be noted that this result carries a rather surprising implication—that, with increasing nutrient supply, raising the percentage nutrient content within the plant takes precedence over utilization of the increased uptake for further growth; it is clear, however, that in any case where such relationships obtain diagnostic plant analysis would be useless over the range where nutrient content is at its maximum level.

Another possible type of relation between nutrient supply and internal nutrient concentration, which would to some extent invalidate the diagnostic use of plant analysis, would include all those in which the same nutrient content might be situated on both an ascending and a descending limb of the curve—that is, where with increasing nutrient supply the internal nutrient concentration reaches and passes a maximum or minimum value. That this may sometimes happen is suggested by the work of Piper (1942) on copper deficiency in oats, and by some of the early work on the nitrogen content of cereals. Piper suggests, however, that the rather higher copper content of plants grown with the lowest copper supply level than that of those receiving a little more was due to the immaturity of the former when harvested, and that, if both had been harvested at a comparable stage of development, the copper supply would have been reflected faithfully in the copper content of the plant material.

In relation to the numerous proposals for using plant analysis to determine the fertilizer requirements of soils for future crops, a further possible way in which the technique might break down can be envisaged. In cereals, for instance, as already stated, after ear formation is well advanced further additions of nitrogen-containing materials cause no increase in yield, although they increase the percentage of nitrogen in the plant. Thus a given final nitrogen content may be the result of a nitrogen supply that increased sharply during a late period of development from a previously low level, or may be the result of a moderate level of nitrogen supply throughout development. In the latter case, the yield will be higher and the yield response to added nitrogen lower than in the former case. In fact, were such differences in the course of seasonal changes in nitrogen supply to occur, the usual relationship might even be reversed, and the higher final nitrogen content be found in those plants that would have responded more markedly to extra nitrogen supply at the beginning of growth. Since, however, cereal soils shew very marked and consistent decline in nitrogen supply level during the growing season, this is unlikely to be a source of difficulty in practice.

Certain other circumstances have from time to time been adduced as diminishing the possible value of plant analysis as a diagnostic procedure. The first of these is the existence of " luxury consumption " ; it has been argued that the fact that a plant may continue to accumulate a nutrient to a level far above that giving the maximum favourable effect on yield prevents the observation of an increase in nutrient content being any indication that this increase has been accompanied by or responsible for an increase in yield. As far as it goes, this statement is of course true ; but to argue from this that " luxury consumption " might interfere with or invalidate the diagnostic use of plant analysis, as has been done by Hanamann (1904), Nolte (1927) and Hardy (1937), is unjustified ; its existence certainly prevents the relation between yield and internal concentration of nutrient being linear over the whole range, but so long as adequate standards for the relationship between nutrient percentage and increase in yield as a result of treatment have been set up, " luxury consumption " is irrelevant to nutritional diagnosis.

It has also been argued (Hall, 1905 ; Münter, 1919, 1920, 1920a) that the fact that plant composition is greatly affected by seasonal variations in weather—often more than by manurial treatments—reduces very greatly its value for diagnostic purposes. This may be true if it is required to provide indications of permanent soil characteristics ; but, if plant analysis is regarded as providing an index of the state of the plant analysed rather than of the soil, this fact need in no way be a disadvantage—rather the reverse. Such differences in composition are often associated with real differences in the potential responses of the plants to manurial treatments, and so long as the relationship between such potential responses and plant composition remains unaffected by seasonal variations in weather the value of plant analysis for diagnostic purposes is in no way diminished by such observations.

# SELECTION OF A TECHNIQUE

The investigator entering for the first time upon the use of plant analysis for the diagnosis of the nutritional status of a particular crop plant has a very wide choice of possible alternative techniques to adopt—the various times during the season at which samples may best be taken ; whether the whole plant should be gathered or some particular organ ; whether the analysis should be conducted on the whole plant material or an extract of it ; for the whole of the element in question or some particular chemical fraction ; and finally how best the analytical results when obtained may be interpreted—all these are questions on which decisions have to be made, and here, as has been shewn, theoretical considerations give little guidance.

Many investigators have tacitly ignored these questions ; a certain technique has been arbitrarily selected and, since it has yielded results, has been continued without regard to the possible improvements which might result from modifications. These investigators have often been satisfied if their method suffices to shew an increase in the content of a nutrient following the application of an appropriate fertilizer—quite apart from the effects of such treatments on yield, or of the relative importance of the different nutrients in the fertilizer mixture. Such a criterion may be valid if the nutrient supply from the soil is the principal subject of interest, but has obvious shortcomings if the method is intended to determine quantitatively fertilizer requirements. As already indicated, the correct criterion for assessing the value of any method purporting to be applicable to the determination of fertilizer requirements is the agreement between forecast and actual yield responses to fertilizer treatment. If the adoption of a technique, however arbitrary, can be supported by evidence of this kind, the question arises whether it is worth while to attempt its improvement. It needs to be pointed out that the labour and time required to make a satisfactory comparison between different possible techniques is very considerable. Consequently, if standard values (see pp. 92-106) have already been ascertained, an attempt to improve the method may well be unjustified, unless a comprehensive investigation over a number of years is in view. On the other hand, if the standard values have not yet been determined, little additional effort may be required to include more than one possible technique in the experiments to determine such standard values, and subsequently only that technique need be employed which has given the most satisfactory results in the preliminary work. A further point to be remembered, when considering to what extent the effort necessary to improve a technique is remunerative, is that the best technique for the determination of fertilizer requirements is likely to differ as between different nutrient elements and may even vary with the amount of the fertilizer application the effect of which is to be predicted ; in practice a compromise may become necessary.

Of those workers who have not arbitrarily selected a diagnostic method, some have attempted to decide on *a priori* considerations in favour of one or another technique, but the arguments put forward can usually be confronted by others supporting another conclusion ; for instance, it has been urged that the older leaves should be selected for sampling, since under conditions of nutrient deficiency a considerable proportion of their nutrient content is translocated to the growing regions, while on the other hand that meristematic regions should be analysed since it is there that differences in nutrient content exercise a direct influence on growth. Other workers have proceeded on the assumption that those sampling and analytical techniques giving the greatest differences (absolute or relative) between plants differing in nutrient status will be the most satisfactory ; this criterion will be discussed at greater length later. Still other investigators have attempted to use criteria such as the correlation of the analytical data with results of soil analysis by some accepted method, or with the total nutrient content of the plant as a whole ; it is clear, however, that in relation to fertilizer needs such criteria can only be of indirect value, depending upon the correlation of soil analysis or the nutrient content of the whole plant with fertilizer needs. Some workers have judged the value of a method for nutritional diagnosis

on the basis of the relation of the concentration of a nutrient in the plants to growth or yield ; this is justifiable where one can be satisfied that differences in the uptake of one nutrient only are responsible for the differences in behaviour of the plants—otherwise, as shewn on p. 57, the relationship cannot be expected to persist.

In view of the considerations put forward it is clear that the value of any method for determining fertilizer requirements from data of plant analyses depends upon the accuracy with which the response to fertilizer additions can be forecast. That is, the primary need is knowledge of the relation between the actual observed yield increment resulting from the treatment and predicted values based upon plant composition.

It is evident that a prerequisite for the application of this criterion is a series of comprehensive experiments in which plant material samples have been taken for analysis *before* the fertilizers, whose effects are to be predicted, have been applied. If the purpose of the diagnosis is to find the fertilizer requirements for crops subsequently grown on the same soil, this involves the determination of yield responses for a crop following that from which the analytical samples have been taken. In fact, few such data are available (for examples, see Wagner, 1915), and have never been used for the purpose indicated. It is true that data have frequently been presented on the composition and yield responses of plants which had received various fertilizer treatments at the beginning of growth, but the relevance of such data depends on the correlation of the yield response of one crop with that of another crop grown subsequently on the same soil—and such correlations are far from perfect.

In the comparison of various possible techniques, however, the varying conditions from year to year are likely to affect conclusions as to the relative value of different techniques to a much smaller extent than the actual level of standard values determined, and hence data of the type described can probably be applied much more usefully for such comparative purposes than for obtaining standard values relating plant composition to prospective yield increase following applications of fertilizer. The advantages of artificial culture methods, either in sand or solutions, indicate their use for comparing techniques, though their dissimilarity from conditions in the field will restrict their use for determining standard values. It hardly needs stressing that the data collected for selecting a diagnostic technique, whether in artificial culture or in the field, should, if possible, cover the whole range of conditions to which it is intended the technique should subsequently be applicable.

Most investigators are not in a position to set up special trials with a wide variety of conditions in which responses can be observed and samples for analysis collected according to the various techniques which it is proposed to test. Most often they are obliged to rely upon samples taken from fertilizer trials already established with other purposes in view. They may be able, in such a case, to treat the varying conditions, other than the supply of the nutrient under consideration, as providing separate units of data from which correlations of the type indicated above may be computed. The more usual procedure is to compare the composition of those plants receiving and not receiving the nutrient in question, and it is argued that the method whose results shew the most marked difference between these two groups of plants is to be preferred. But this argument may be fallacious, if either the standard error or the coefficient of variability of the analytical results obtained on replicate samples under the different methods are different, which may often be the case. Data of Pfeiffer *et al.* (1912), for instance, shew that in oats with intermittent water supply, though the proportional increase in the nitrogen content of oat straw with added nitrogen is considerably greater than that in the grain, the coefficients of variability for the former figures are so much higher as to make the grain composition a more trustworthy index of response. Nevertheless, when no other criterion is available, this test of the proportional increase in nutrient content may be of some value—where, for instance, a perennial crop is concerned for which the establishment of *ad hoc* fertilizer trials on a large scale is impracticable—especially if the method of analysis employed involves a large and fairly constant coefficient of variability, as is the case with many colorimetric and spectrographic methods.

A modification of this approach which would have rather better justification but which, so far as the authors are aware, has never been used, would be to compare, instead of the differences between treated and untreated plants, the ratios of these differences to their standard errors ($t$ values).

Where yield response and nutrient content data are available the techniques of correlation and regression can usually be fruitfully applied. A warning needs to be given, however, against the uncritical acceptance of results by the standard correlation technique. This technique is devised for estimating the relationship of two quantities *linearly* dependent upon one another—and we have seen that there is no reason to suppose that the relationship between yield response and nutrient content is linear. Accordingly, account should be taken of the possibility that the relationship is curvilinear ; since no assumption can be made on the form of the curve, it is probably best to try to fit a polynomial expression :—

$$y = a + bx + cx^2 + \ldots\ldots$$

where $y$ is the yield response, $x$ the nutrient content, and the remaining terms constants. Where data on simultaneous variation in more than one nutrient are available, the values may be analysed by the method of multiple regression—the possibility being again borne in mind that the relationships with the different nutrients may shew independent curvature.

It is necessary at this point to refer to the arguments brought by Thomas and Mack (1944a) against the use of statistical methods in interpreting the results of analytical diagnosis. They argue that " the use of calculations of probability in such a manner as to submerge or include specific and particular properties of individuals, such as leaf composition, into an abstract quantity is opposed to the whole spirit of biology and is logically not permissible". They appear to regard as inacceptable the lumping of data from similarly treated plots, whether of yields or of chemical composition. They do not appear to realize, however, that this consideration applies with equal force to individual plants within a plot as to replicate plots ; they sample for analysis only those plants which appear typical of the plot, and yet their yield data presumably derive from all the plants on the plot. It may be admitted that for the purpose in view the random variation of yields from replicate plots about their mean value may provide further data for ascertaining the relation between plant composition and prospective yield, since it may be anticipated that these variations in yield may be highly correlated with plant composition, and, if so, this relation can be determined from such data for replicated plots, though perhaps not so accurately as from individual plants. Where data are available for individual plots or plants of both plant composition and yield, use would naturally be made of all such individual groups of data for assessing the relation sought, and not of treatment means only. This does not circumvent the use of the appropriate statistical methods for determining the magnitude and significance of the relation, for without such tests it is impossible to determine whether the observed differences in yield and chemical composition are consistently related.

The error of a technique of analytical diagnosis may be conveniently divided into three portions :—that of the analytical procedure, that of the sampling method, and that of the standard values.

With standard chemical methods the analytical errors will generally be negligible compared with the errors from other sources (if the analytical error is one-fifth as great as the total error, its complete removal will only reduce the latter by some 2%), but with some of the rapid methods in current use it may make an important contribution to the total error.

The errors of sampling need no further comment. By including in the sample for analysis material from an appropriate number of plants distributed over the area under study, they can be brought to a satisfactorily low level.

The errors of the standard values are much more complex, and include those involved in the determination of the relations between plant composition and yield response to fertilizer in the experimental data collected for this purpose, and those due to differences between the conditions prevailing during the growth of the standard plants and of plants in other investigations. The first group of errors will be systematic—that is, they will have similar effects on all diagnostic conclusions ; the second group will also be systematic in so far as they may be ascribed to deviations of the conditions under which the standard values were obtained from the mean of the range to which it is intended they should be applicable. These systematic errors can be reduced by increasing the number and range of experiments on which the standard values are based. The remaining portions of this group of errors will probably be random, like those due to sampling and the analytical methods.

To summarise the preceding paragraphs : the only satisfactory basis for comparing the relative value of different possible techniques for analytical diagnosis is the deviation of the various estimates of increase in yield following a given fertilizer treatment from the actual increase observed when the same treatment has been applied subsequently to the time of sampling the plants for analysis. When this criterion cannot be applied, the yield responses to treatment applied prior to sampling (though at the proper time of year or stage of development) will provide fairly satisfactory data. If yield response data are not available, some idea of the relative value of different indices of nutrient status may be obtained from the absolute or relative differences (or, better, their ' t ' values) in these indices between plants under different conditions of nutrition.

## SELECTION OF PLANTS FOR SAMPLING

Where the purpose of diagnostic plant analysis is the determination of the characteristics of the soil with a view to modifying the fertilizer regime for future crops, it may be necessary to determine what plant species provide the best indication of fertilizer requirements. Oats was selected by many of the early investigators, some giving as the reason that it was normally grown after the soil had been to some extent exhausted of phosphorus and potassium by previous crops in the rotation (Stahl-Schröder, 1904). In regard to copper deficiency in Australia, Teakle and his collaborators (Teakle, 1942 ; Teakle and Turton, 1943 ; Teakle, Thomas and Turton, 1941) found that oats, subterranean clover, vine, pear and apple were suitable plants to sample, though many other plants gave no reliable indication of the copper status of the soil. Robinson and Edgington (1942) found hickory leaves more suitable than those of other species for determining the boron status of soils, partly because they showed wide variations in composition, partly because they were little liable to soil contamination. But the selection of plants for analysis in such cases is often likely to depend upon which species are present rather than which are most suitable.

Where the problem is the correction of unsatisfactory nutritional conditions in the crop actually sampled, the selection of a suitable species does not, of course, arise. It is still necessary, however, to consider on what principle to select the individual plants—a decision also necessary where the nutrient status of the soil, rather than of the plant, is in question. If the yield response of a crop to fertilizer treatment were linearly related to the nutrient content in the material analysed, the matter would be relatively simple, for a random sample of the plants would give a correct indication of the response of the field as a whole. Where, however, luxury consumption occurs, this will not be true, for a random sample from a field in which some of the plants only are suffering from a nutrient deficiency will very probably contain enough material from plants in the luxury consumption range to push the mean nutrient content of the whole bulked sample into this range (Ulrich, 1943). Such observations have been made on apple, for instance, by Burrell *et al.* (1942), and this may well account for the irregular relationships between leaf scorch and potassium content of plum leaves found by Boynton *et al.* (1941). Some investigators, notably those of the " foliar diagnosis " school (see p. 41), recommend that samples should be taken from plants appearing typical of the area covered ; Clements and Moriguchi 1942), in their work on sugar cane, sampled " *selected* plants representing the average of the stand " ; Bathurst (1944a), too, in taking samples of citrus leaves, advises that they should be taken from trees " representative of the block as a whole". This procedure, of course, involves a subjective estimate of what is typical or representative, and therefore may, to some extent, be distrusted ; moreover, it hardly covers the possibility of the area bearing a minority of plants with a deficiency among others with satisfactory nutrition.

It seems clear that, in order to obtain a clear idea of the range of nutritional conditions in the field or plantation, it will be necessary to take more than one sample, and to analyse each separately. Whether the separate samples are to be taken as representing different topographical divisions of the area (Yuen and Hance, 1939 ; Chem. Dept. Exp. Sta., H.S.P.A., 1944 ; Ulrich, 1944) or different types of growth of the plants (Bathurst, 1944a) is a matter that can hardly be decided without reference to the particular problem ; where the latter procedure can be used on a tolerably objective basis, it is probably to be preferred. There seems, in any case, to be no reason to take replicate random samples covering the whole area.

## TIME OF TAKING SAMPLES

### Time of Day

Certain investigators have restricted the taking of samples for diagnostic analysis to a particular time of day. For rubber Chapman (1941) recommends that leaf samples should be taken between 6 a.m. and 10.30 a.m. ; Mitchell and Chandler (1939) in their studies on forest trees preferred the mid-day period, 9 a.m. to 3 p.m. Nightingale's (1942) sampling of pineapple leaf bases took place between 8 a.m. and 4 p.m., while the Hawaiian Sugar Planters' Association (Chem. Dept. Exp. Sta., H.S.P.A., 1944) recommend that samples of sugar cane leaves should be taken during the first three hours after sunrise.

Few observations have been made on diurnal variation in the nutrient content of plant tissues. Schulze and Schütz (1909), Otto and Kooper (1910) and Pigorini (1914) found a decrease in the percentage nitrogen content in the dry matter of leaves overnight, while Kosutany (1897), Suzuki (1897) and Chibnall (1922) found increases in nitrogen content during the night. Ingalls and Shive (1931) found that the iron concentration in the sap of several species, especially succulents, increased during the day by as much as 40% of its mean value, and decreased again at night. McCool (1926) found the concentration of phosphate in the expressed sap of various plants higher during the morning than after mid-day. Penston (1935, 1938) found diurnal variations in the potassium content of potato leaves between 2.5 and 4.1%, and in maize leaves between 3.7 and 4.9%. Chapman (1941) stated that diurnal variation in mineral content occurred in rubber leaves. Bolas and Goodall (1937) found variations of up to 30% of the mean value in the ash content of tomato leaves during a 24-hour period, while Woodward *et al.* (1944) found the ash content of lucerne hay varied by as much as 40% of the mean with the time of day. Phillis and Mason (1942) found that the percentage content in cotton leaves of most of the mineral elements they studied decreased by day, but increased during the night. These results suggest that some control of the time of day at which samples are taken is desirable, but do not suggest any particular time as being preferable to others. Fonder (1929a) found variations of up to 25% in the calcium content of lucerne during the day ; since variation was least marked between noon and 4 p.m., this period was recommended for sampling. Scarseth (1943), found that a plant suffering from inadequate nitrogen supply contained virtually no nitrate in the afternoon, though some was present in the early morning—indicating that later sampling may be preferable.

### Time of Year or Stage of Development

Under this general heading also, the time of year at which samples are to be taken must be considered. For annual crops, when it is intended that the detection of unsatisfactory nutritional features shall be followed by corrective treatment of the same crop from which analytical samples were taken, the possible period over which samples can be taken is necessarily restricted to the period during which fertilizer treatments will be effective. In the choice of a sampling time it is necessary to take into account not only the accuracy of forecasting yield responses at different times, but also the actual extent of such potential responses at the same time. Consequently the tendency will be for sampling to take place as early as it can give definite indication of deficiency (Craig, 1939 ; Burkhart and Page, 1941).

Where the purpose of the sampling is to indicate treatments required by subsequent crops on the same soil, the criterion of correlation of analyses with yield responses will hold, except in so far as considerations of convenience enter. Although the proportional differences (or their errors) between analytical data for different fertilizer treatments have been used as evidence to decide the best stage for sampling, in annual crops at least it is a very doubtful criterion for this purpose, since these proportional differences are likely to be largely dependent upon seasonal changes in the availability of the fertilizer material. This objection does not, of course, apply to comparisons of plants grown on soils naturally well and poorly supplied with the element in question, and is less applicable to perennials, with their stored reserves of nutrients, than to annuals.

The problem of the best time for sampling is complicated by the seasonal variations in soil nutrient supply. As a result of these variations, the most appropriate stage of development may not be the same for widely different soil types or climates. The optimum time of sampling

may also be expected to differ for different nutrient elements, so that a single time cannot be optimal for all. Thus, in respect of time of sampling as well as many other points, it can only be hoped that the technique adopted falls within a fairly wide range around the optimum, and not that the absolutely optimal conditions can be found.

As indicated above (p. 56), theoretical considerations suggest that, in annual plants of the cereal type, analysis of samples taken early in the development of the plant may give the best indication of nutritional status. Crowther's (1941) observations on cotton grown on the same plot in successive years supports this, but his earlier (1937) comparisons of manurial trials shewed that the relative difference between nitrogen concentration in leaves from high nitrogen and low nitrogen plots increased to 140 days from germination, as also did the correlation of these nitrogen percentage data with yield responses at the various sites (omitting the aberrant result at Biba, $r = -0.343$ at 60 days, $-0.660$ at 140 days ; $n = 8$). Nevertheless, a number of other observations support the use of early samples. Chapman (1935) found that the response of oats to phosphorus supply in pot culture (measured as total dry weight) was highly correlated with the inorganic phosphate content of different parts of the young plants, but that at the heading stage such correlations were much less marked and at ripening absent. Fraps *et al.* (1937) found the correlation of nutrient content of oats with soil supply better during early growth than as maturity approached. Salter and Ames (1928) found that the differences in nutrient content of maize plants with varying fertilizer treatment were greater at early stages of growth, and concluded that young plants might give better indications of soil productivity than older ones ; since, however, the supply of all three principal fertilizer elements was varied simultaneously, this conclusion can only be accepted with reserve. Beath *et al.* (1939), in their investigations on selenium, found that differences in the percentages of this element in indicator plants were more marked at early stages of development. Forster (quoted by Teakle, Thomas and Turton, 1941) found that zinc deficiency in oats could only be detected by analysis if the samples were taken early in development, and Teakle, Thomas and Turton (1941) came to the same conclusion in regard to copper deficiency.

Burström (1937), in selecting a stage at which samples should be taken, proceeded on the assumption that under field conditions some variation in the sampling stage was inevitable, and that consequently a stage should be chosen at which such variation would have little effect on the analytical results (c.f. Stahl-Schröder, 1904—referred to on p. 15) ; this criterion was satisfied for oat leaves by the period between panicle emergence and flowering. Lundegårdh (1941) found that the relation of composition at this stage to growth was more constant than at an earlier stage.

It will be noted that, in the above paragraphs, the discussion has been mainly on the *stage of development* at which samples should be taken, and not of the *date*. If a date were to be specified instead, the relation between composition and yield response would be more likely to be affected by extraneous factors such as weather than if sampling occurred at a particular stage of development, irrespective of when this stage was reached.

For perennial crops, the purpose of analytical diagnosis is generally to remedy unsatisfactory conditions during the course of the following season, so that the choice of a sampling date need not be impeded by the need to obtain a result early enough to enable treatment to be carried out that same season. Some investigators have used the same criterion as that of Burström above ; Mitchell (1936a), for instance, preferred the last two or three weeks before yellowing for sampling forest tree leaves, for this reason, while Boynton and his collaborators (Boynton *et al.*, 1940 ; Reuther and Boynton, 1940) found that the composition of apple leaves was most constant during late July and August. In California it was found (Chapman and Brown, 1943a ; Chapman *et al.*, 1944) on this basis that July, August and September were the best months for sampling citrus leaves ; on the other hand, Bathurst (1944a) preferred the winter (May-July in South Africa) for the same reason. Lilleland and Brown (1939) advised that plum leaves should be sampled before August, since at that time migration of potassium from leaves adequately supplied with that element commences ; in peach, June and July were considered to be the period of greatest constancy in composition (Lilleland and Brown, 1941). McCollam (1943, 1944) found that in the vine, citrus and peach the middle of the growing season was the best period for taking leaf samples, since earlier the mineral content tended to be uniformly high,

and later uniformly low. Baker (1943) and Goodall (1945a), however, shewed that the differences in potassium content of apple leaves are more marked in September than at flowering time, and Goodall (1945) also found that the differences in magnesium content between leaves from deficient trees and from others absorbing adequate magnesium increased from July to October. Drosdoff (1944) in tung likewise found the differences in potassium content of the leaves greater in October than in July or August. In respect of nitrogen content, Nasharty (1944) found that differences in peach leaves increased during April and May ; but the data of Frear and Anthony (1943) suggest that the nitrogen concentration in apple leaf samples taken in May may indicate the nutritional status of the trees better than ones taken later.

Many investigators have avoided the selection of the most appropriate time of sampling by taking samples on several occasions through the season. This procedure reduces the risk that effects of differences in the seasonal course of nutrient supply may pass unnoticed (Epstein and Lilleland, 1942), but it may considerably increase the difficulties of interpreting the results. The " foliar diagnosis " school have on several occasions (Lagatu and Maume, 1924, 1924a ; Thomas, 1938b ; Thomas and Mack, 1939c) suggested that optimal nutrition is associated with a linear course of change during the growing season in the proportions between the bases potassium, calcium and magnesium in the leaves. The same idea has also been extended (Lagatu and Maume, 1925 ; Thomas *et al.*, 1944) to the proportion of nitrogen to phosphorus. In spite of the fact that the taking of several successive samples is a central feature of the " foliar diagnosis " technique, its advocates have often been content to report only the mean values for these successive samples, and have even admitted that a single sample may often give sufficient information (Thomas *et al.*, 1942). Analysis of samples taken on several successive occasions may, however, be essential if such analyses are to be used to determine the date and amount of fertilizer applications during the growing season. Proposals of this sort have been made for sugar cane by Yuen and Hance (1939) among others, for tomato by Emmert (1941, 1942a), for pineapple by Nightingale (1942, 1942a), and for grapefruit by Finch (1944) and Jones (1944).

## ORGAN OF PLANT TO BE SAMPLED

The possibility cannot be excluded that analysis of the whole plant would provide the best index of nutritional status. It has, indeed, often been argued that, since the plant consists of organs differing greatly in composition, the effect of variation in the proportion of the plant formed by the various organs will be eliminated by confining the analysis to a particular organ, and thus the accuracy of estimation will be increased (Heinrich, 1882 ; Atterberg, 1901 ; Alway, 1928). It must be remembered, however, that the proportion of the different organs is itself affected by the nutritional status of the plant; hence it is hardly possible by such facile, *a priori*, arguments to reject analysis of the whole plant in favour of analysis of separate organs—it is a question which should be resolved by direct experimentation.

Attempts have also been made to select single organs on a basis of *a priori* considerations. It has been reasoned, for instance, that the conducting tissue, since its composition is likely to be closely related to the current nutrient intake of the plant, is also likely to provide the best index of response to immediate nutrient application. The view that the composition of the tracheal sap is related to current nutrient supplies is undoubtedly correct, but to argue from this that it also provides the best index of response can be little more than guessing, and in many cases may be untrue. It has also been argued that, since the leaves are the organs of active assimilation, their composition must be the best basis for estimating the nutritional status of the whole plant.* But nutrition can affect the growth and yield of the plant in many other ways than by direct effects on assimilation, important as these may sometimes be—and even where an unsatisfactory nutritional condition affects the yield by reducing the assimilation, it is quite

* For instance, " In the life of a growing cane crop, from its earliest stages to its maturity, the major chemical activity in the plant takes place within the leaf tissue. It was believed, therefore, that absorption of plant nutrients from the soil by the crop should be reflected from time to time by changes in the relative or total amounts of absorbed nutrients and moisture found in the leaf tissue of the plant." (Hance, 1937). " The leaf is usually considered best because it is such a vital part of the plant in its nutritional processes. It is in the leaf that the plant foods are gathered and combined for redistribution throughout the plant." (McCollam, 1944).

conceivable that analysis of some other part or of the plant as a whole would provide a more sensitive index of the nutrition than analysis of the leaf itself.

When experimental evidence has been brought forward to support the choice of one or other organ for sampling for diagnostic purposes, it has generally been on a basis of proportional (or absolute) differences between plants at different levels of nutrition. For instance, for the diagnosis of boron deficiency in apples, fruits are preferred to leaves for this reason (Askew and Thomson, 1937). Brandenburg (1939) found leaves of beet preferable to roots in this respect, and Burkhart and Page (1941) found the range of calcium concentration in the hot water extracts of peanut material from fertilizer trials to be greatest in the middle and lower leaf blades, that of potassium in the younger petioles, and that of magnesium in the older petioles ; it is interesting to note that a similar argument was used by Heinrich (1882—see pp. 12, 13) to support his practice of sampling cereal roots. Sometimes even the low percentage content of a nutrient element in an organ has been cited as an argument against its use—for instance, that of nitrogen in the leaf sheaths of sugar cane by Clements and Moriguchi (1942) and potassium in the grain of oats by Atterberg (1888, 1889); this consideration is valid when only an insensitive method of analysis is available, otherwise it implies that the errors of the analytical results between replicate samples are similar for all organs irrespective of their mineral content.

Where data are available on the variability of analytical results for different organs, a more satisfactory basis exists for the choice of one or other organ for diagnostic purposes. The data of Bartholomew *et al.* (1933), for instance, shew that both the extent and the significance of differences in nitrogen content of tomato plants with varying nitrogen supply are greater in the stems than in the leaves. Ulrich (1942, 1942a, 1942b) found that, in the grape vine, both the potassium and nitrate concentrations in the petioles varied more with varying nutritional conditions than in the leaf-blades, and moreover these differences were more highly significant ; hence the petioles were regarded as providing more satisfactory material for diagnostic purposes. Harrington (1944) obtained similar data supporting the use of petioles rather than leaf laminae of spinach for diagnosis of the nutritional status with regard to the three principal nutrients, and also found that the response to a change in supply was more prompt in the petioles. In pecan leaves, on the other hand, Gossard (1943) found that not only was the nitrogen content lower in the rachis than in the leaflets, but also its coefficient of variation was greater and the proportional difference between samples from areas of different nutritional status was less ; these lines of approach thus rightly led to the choice of leaflet rather than rachis samples for the diagnosis of nitrogen deficiency.

When the general type of organs to be sampled has been decided, leaves, stems, or petioles, it remains to be considered how accurately the sample type needs to be defined—whether, for example, a leaf at a particular morphological level should be selected, as is done by the " foliar diagnosis " school (see p. 41), whether all the leaves of a certain number of plants should be gathered, as is done by Lundegårdh (1941), or whether a random sample of the leaves should be taken. Since differences in age and morphological position have been shewn to be accompanied by considerable differences in composition, it seems probable that random sampling will be unsatisfactory since these differences will unnecessarily be included among the sources of error. In his study of the nitrogen content of pecan leaves, Gossard (1943) confirmed that the error of random samples of leaves was greater than that of samples selected on criteria of morphological position, size and age. On the other hand, although Wallihan (1944) found differences in composition between different types of leaves in the sugar maple, he considered a random sample from the most accessible part of the crown would be as representative as any planned selection of leaves. Where the age of leaves (or other organs) to be sampled for analytical diagnosis of a particular deficiency is in question, knowledge of the mobility or immobility of the nutrient within the plant may be usefully applied. If it is known that under conditions of deficiency an element is readily remobilized from the older parts to supply the needs of the newly developing organs, there is a reasonable probability that the former will provide better indices of deficiency (Remy, 1903, 1903a ; Nightingale, 1942a). This is outstandingly the case with potassium, and less markedly so with nitrogen and phosphorus. Calcium and boron, on the other hand, are not at all readily remobilized, and hence differences in the current ability of the plant to respond to these elements may be more markedly reflected in the composition of the younger parts. As

between different organs of the same type, those which first shew symptoms of deficiency are likely to be those shewing the greatest variations in composition with differences in nutrient supply—thus, symptoms of potassium deficiency generally appear earliest and most clearly on the older leaves, those of boron deficiency in the apical regions (Hambidge, 1941).

In considering which of the various petioles of a sugar beet plant to sample for diagnostic purposes, Brown (1943) used an argument analogous with that of Burström (1937) in relation to the time of sampling; since the variations in petiole composition with position in the crown were least in the leaves of medium age, and since in their selection the personal factor in sampling would thus be least important, these were considered the most suitable for sampling. Similarly, Lineberry *et al.* (1944) preferred mature leaves of strawberries to younger leaves of either crown or runners, because it would be difficult to eliminate the effect of age differences in the latter.

Roach (1945) has put forward, in favour of sampling younger rather than older leaves, the argument that they will be freer from contamination, which may be of importance where certain trace elements are concerned. He also suggested that, by taking samples of young leaves at a constant stage of development, difficulties arising through differing age of leaves at different times in the growing season could be eliminated; however, Richards (1932) has shewn that successive leaves of barley, sampled at the same stage of development, differ greatly in potassium content.

In trees, not only does the question of leaf age arise, but also the morphological position of the leaves to be sampled; the two are to some extent related. Among the investigators who have analysed different morphological types of tree leaves, and have found differences in their composition are Larson (1933), Warne (1934), Fudge (1938, 1939), Kidson *et al.* (1940), Wallace (1940), Reuther and Boynton (1940), Chapman (1941), Goodall (1943, 1945, 1945a) and Wallihan (1944). Sometimes these differences may be ascribed to the proximity of developing fruit (Larson, 1933; Fudge, 1938, 1939), but more often they are associated with differences in leaf age. Kidson *et al.* (1940) found that the range of magnesium content in apple trees showing various degrees of magnesium deficiency was greater in the lower than the upper leaves of the leader shoots. Goodall (1943) found that the proportional difference in potassium content between apple trees differing in potassium status was greater in spur than shoot leaves sampled in the autumn.

If the plant shews deficiency symptoms on some of its leaves only, the question may be put whether such leaves or others which appear healthy should be preferred for diagnostic purposes. There is some evidence (Parbery, 1935; Hardy, 1937; Boresch, 1938; Fudge, 1938, 1939; McGeorge, 1939; Reuther and Boynton, 1940; Southwick, 1943; Goodall, 1945) that in such cases the concentration of the deficient nutrient is lower in the affected leaves than in others from the same plant, though it is not clear in all these investigations that the leaves were comparable in age and morphological position. The concentration of other nutrients in the leaf may, however, also be affected by the presence of deficiency symptoms (Goodall, 1945), which suggests that to restrict the sample to healthy leaves, as has frequently been done (Reuther and Boynton, 1940; Drosdoff and Painter, 1942; W. A. Roach, private communication) may sometimes prevent a mistaken diagnosis.

Some investigators have recommended sampling only part of the leaf lamina. In Hawaii, several investigations on sugar-cane (Hance, 1937; Nishimura and Hance, 1938; Yuen and Hance, 1939; Borden, 1942, 1944; Chem. Dept., Exp. Sta., H.S.P.A., 1944; Doi, 1944) have involved the use of a leaf punch, to remove small discs of tissue from a number of leaves; a leaf punch has also been used by the Montpellier workers on grapevine leaves (Lagatu *et al.*, 1932). This is a very convenient method of taking samples, but the danger of contamination must be remembered if the material is to be used for trace element determination. Emmert (1931) has presented some evidence that in lettuce the composition of the leaf edge reflects the nutritional status of the plant better than that of the more central part of the lamina. In the pineapple, as already mentioned, Nightingale (1942, 1942a) sampled only the meristematic bases of the leaves. In general, however, it is doubtful whether such refinements as restricting the sample to a particular part of the lamina are worth while, especially if slight variation in the line of separation may alter the proportion of tissues and hence the percentage of nutrients in the sample.

The optimum type of sample may not be independent of varying external conditions. Since

changes in light, temperature and water supply affect the distribution of nutrients among the organs, they may result in one organ providing a more reliable type of sample in one year, another in the following year. Hence, where possible, it is desirable to base deductions as to the optimum type of sample on observations in several years or under a wide range of conditions. The optimum type of sample at different stages of development may well not be the same (Gilbert and Hardin, 1927). Drake and Scarseth (1940) have shewn that the distribution of potassium in the tobacco plant is such that the younger leaves provide a better index of differences in the level of supply when it is low, while at higher levels the older leaves give more reliable indications; similarly the data of Gauch and Wadleigh (1945) with kidney bean shew that the increases in sodium content with increasing additions of sodium chloride to the medium are more marked in the roots at lower levels of supply, but in the stems at higher levels. Thus a single type of sample cannot be universally optimal, and it is probably hardly worth while to go to great trouble to identify this optimum.

There is in the literature a fair amount of data on the composition of different organs under varying nutritional conditions, with the yield responses of similar plants to fertilizer treatment. Recalculation from such data would sometimes enable a decision to be reached on which organ should be sampled without recourse to *ad hoc* experimentation—though always with the reservation mentioned above (p. 62) in relation to annual crops, that the yield response of a plant can never be a sure guide to the response of the same species when grown on the same site later. Among the sources of such data may be mentioned Stahl-Schröder's (1904) experiments with oats, Ames's (1910) experiments with wheat, those of Pfeiffer *et al* (1912) on the nitrogen nutrition of oats, the very extensive observations of Wagner (1915) on barley, mangold, oats, rye, sugar beet and wheat, Münter's work on wheat (1919) and sugar beet (1920), and, more recently, the experiments of Chapman (1935) on phosphorus nutrition of oats and of Lorenz (1942) on boron nutrition of beet.

Very much more abundant in the literature are data which enable comparisons to be made of the differences in composition of different plant organs with varying levels of nutrition. Unfortunately, only too rarely are the analytical results from replicate samples (or the errors between them) reported—very commonly, samples from replicate plots in a manurial trial are bulked for the purpose of analysis. Consequently, to most of these data the more satisfactory test of the coefficient of variability of the differences (p. 62) cannot be applied. In Table IV are indicated the organs of many crop plants in which the proportional differences in content (usually on a dry matter basis) of a given nutrient with varying supply of it have been found greatest. Only those sets of data are included in which the differences between organs are marked and tolerably consistent, and where the differences are reasonably ascribable to varying supply of a single nutrient; in some cases this difference is indicated only by the presence or absence of symptoms.

**Table IV.**

**Data relevant to the selection of organs for analytical diagnosis.**

*N.B.—Letters in brackets refer to Notes at end of Table.*

| Plant | Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference |
|---|---|---|---|---|---|
| APPLE (*Pyrus malus*, etc) | | | | | |
| | N | ———— | Leaves | Terminal shoots, fruit pulp | Wallace, 1930, 1938 |
| | N | ———— | 2-year twigs | Leaves, 1-year twigs | Gildehaus, 1931 |
| | K | ———— | Leaves | Twigs, fruit pulp | Wallace, 1929a |
| | K | ———— | Leaves | Twigs | Gildehaus, 1931 |
| | K | Various | Leaves | Bark | Chandler, 1936 |
| | K | Late autumn | Leaves | Bark | Batjer & Degman, 1940 |
| | K | Sept. | Spur leaves | Shoot leaves | Goodall, 1943 |
| | Mg | Feb.-Mar. (C). | Older leader leaves | Leader tip leaves | Kidson *et al.*, 1940a; N.Z. Dep. sci. industr. Res 1942 |
| | B | Harvest | Fruit | Leaves | Ferguson & Wright, 1940 Batjer & Haller, 1942 |

| Plant | Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference. |
|---|---|---|---|---|---|
| APRICOT (*Prunus armeniaca*) | | | | | |
| | B | Oct. | Bark | Leaves, wood | Eaton, F. M., 1935 |
| | B | ———— | Fruit | Leaves, twigs | Eaton, *et al.*, 1941 |
| | Zn | Sept.-Oct. | Stems | Leaves | Chandler *et al.*, 1940 |
| BARLEY (*Hordeum vulgare*) | | | | | |
| | P | Harvest | Straw | Grain | Godlewski, 1901 ; Hall, 1905 ; Wagner, 1915 |
| | K | Harvest | Straw | Grain | Godlewski, 1901 ; Hall, 1905 ; Wagner, 1915 |
| BEET (*Beta vulgaris*) [*see also* Mangold, Sugar Beet] | | | | | |
| | K | Harvest | Tops | Roots | Lorenz, 1942 |
| | Ca | Harvest | Petioles | Leaves, roots | Lorenz, 1942 |
| | B | Harvest | Tops | Roots | Lorenz, 1942 ; Binnie, 1943 ; Gum *et al.*, 1945 |
| | B | Apr.-Aug. | Leaf laminae | Roots | Eaton, 1944 |
| BLACKBERRY (*Rubus* spp.) | | | | | |
| | B | Nov. | Leaves | Stems, roots | Eaton, 1944 |
| BUCKWHEAT (*Fagopyrum esculentum*) | | | | | |
| | P | 47 days from germination | Stems (D) | Leaves (D) | Neller, 1935 |
| CABBAGE (*Brassica oleracea*) | | | | | |
| | B | Apr. | Outer leaf laminae | Inner leaf laminae | Eaton, 1944 |
| CAULIFLOWER (*Brassica oleracea*) | | | | | |
| | B | ———— | Leaves | Stems, heads, roots | Wolf, 1940 |
| CELERY (*Apium graveolens*) | | | | | |
| | P | Autumn | Stalks (D) | Leaves (D) | McCool & Weldon, 1928 |
| | K | Autumn | Stalks (D) | Leaves (D) | McCool & Weldon, 1928 |
| | B | Oct. | Leaves | Crowns, roots | Maier, 1943 |
| CHICORY (*Cichorium intybus*) | | | | | |
| | B | ———— | Tops | Roots | Muhr, 1942 |
| COFFEE (*Coffea* sp.) | | | | | |
| | B | ———— | Old leaves | Young leaves | Tanada & Dean, 1942 |
| COTTON (*Gossypium* spp.) | | | | | |
| | N | Various | Leaves | Flower buds | Crowther, 1936a |
| | K | 10 weeks | Lower leaves | Upper leaves, bark | Phillis & Mason, 1940 |
| | B | Nov. | Leaves | Stems, roots | Eaton, 1944 |
| CUCUMBER (*Cucumis sativus*) | | | | | |
| | Mg | ———— | Lower leaves | Upper leaves, stems, fruits | Carolus, 1935 |
| ELM (*Ulmus americana*) | | | | | |
| | B | Nov. | Leaves | Stems, roots | Eaton, 1944 |
| FIELD BEAN (*Vicia faba*) | | | | | |
| | B | Harvest | Fruit wall | Foliage, seeds | Truninger, 1944a |
| | Mn | Harvest | Leaves | Seeds | Marsh & Powers, 1945 |
| FIG (*Ficus carica*) | | | | | |
| | B | Nov. | Leaves | Roots | Eaton, 1944 |
| FLAX (*Linum usitatissimum*) | | | | | |
| | P | Harvest | Stems | Seeds | Maschhaupt, 1922 |
| | K | Harvest | Stems | Seeds | Maschhaupt, 1922 |
| | Mg | Harvest | Straw | Seeds | Truninger, 1944 |

| Plant | Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference. |
|---|---|---|---|---|---|
| FRENCH BEAN (*Phaseolus vulgaris*) [*see also* Snap Bean] | | | | | |
| | B | Harvest | Foliage | Seeds | Truninger, 1944a |
| GOOSEBERRY (*Ribes grossularia*) | | | | | |
| | Ca | ———— | Stems | Leaves, roots | Gauch & Wadleigh, 1945 |
| | K | June | Leaves | Stems, fruit | Wallace, 1928a |
| GRAPE (*Vitis vinifera* etc) | | | | | |
| | N | ———— | Leaves | Wood, fruit juice, fruit pulp | Wagner, 1907 |
| | N | May-Sept. | Petioles | Leaf laminae | Ulrich, 1942a |
| | K | ———— | Leaves | Wood, fruit juice, fruit pulp | Wagner, 1907 |
| | K | May-Sept. | Petioles | Leaf laminae | Ulrich, 1942, 1943 |
| | B | Nov. | Leaves | Stems | Eaton, 1944 |
| HOP (*Humulus lupulus*) | | | | | |
| | N | June-Sept. | Leaves | Stems | Schneider, 1905 |
| JAPANESE MILLET (*Echinochloa frumentacea*) | | | | | |
| | Mg | 9 weeks | Leaves | Stems, roots, heads | Lutman & Walbridge, 1929 |
| KIDNEY BEAN (*see* French Bean) | | | | | |
| KOHLRABI (*Brassica oleracea*) | | | | | |
| | B | Harvest | Leaves | Roots | Truninger, 1944a |
| LEMON (*Citrus limonia*) | | | | | |
| | P | Winter | Roots | Leaves, stems | Haas, 1936 |
| | Fe | ———— | Leaves | Stems, roots | Chapman *et al.*, 1940 |
| | Ga | Aug. | Roots | Leaves, stems | Liebig *et al.*, 1943 |
| | In | Aug. | Roots | Leaves, stems | Liebig *et al.*, 1943 |
| LUCERNE (*Medicago sativa*) | | | | | |
| | K | ———— | Leaves | Stems | Davies, 1940 |
| | S | ———— | Leaves (with fine stems) | Stems | Alway, 1928 |
| | B | Second cutting | Leaves | Stems | Brown, 1940 |
| | B | July-Sept. | Leaves | Stems, roots | Eaton, 1944 |
| LUPIN (*Lupinus luteus*) | | | | | |
| | Fe | Various | Roots | Tops | Scholz, 1933 |
| MAIZE (*Zea mays*) | | | | | |
| | P | Harvest | Stems | Roots | Craig, 1934b |
| | K | Flowering | Stems | Leaves | Bartholomew & Janssen, 1929 |
| | Mg | ———— | Lower leaves | Upper leaves, stems | Garner *et al.*, 1930 |
| | Mg | Harvest | Leaves | Stems, grain | Truninger, 1944 |
| | Fe | June | Roots | Leaves, stems | Olsen, 1938 |
| MANGOLD (*Beta vulgaris*) | | | | | |
| | N | Harvest | Roots | Leaves | Wagner, 1915 |
| | P | Harvest | Roots | Leaves | Wagner, 1915 |
| | K | Harvest | Roots | Leaves | Wagner, 1915 |
| | K | Harvest | Foliage | Roots | Maschhaupt, 1934 |
| | B | ———— | Leaves | Roots | Brandenburg, 1939 |
| | B | ———— | Tops | Roots | Muhr, 1942 |
| MUSTARD (*Brassica* spp.) | | | | | |
| | B | Harvest | Straw | Seeds | Truninger, 1944a |
| OATS (*Avena sativa*) | | | | | |
| | N | Harvest | Straw | Grain | Atterberg, 1887 |
| | N | Harvest | Grain | Straw | Wagner, 1915 |
| | P | Harvest | Straw | Grain | Atterberg, 1887; Wagner, 1915 |
| | P | Heading and ripening | Lower stems (E) | Upper stems (E) | Chapman, 1935 |

| Plant | Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference |
|---|---|---|---|---|---|
| OATS (*Avena sativa*)—continued | | | | | |
| | P | Harvest | Straw and chaff | Grain | Opitz, 1944 |
| | K | Harvest | Straw | Grain | Atterberg, 1887, 1901; Wagner, 1915; Ehrenburg, 1919 |
| | K | Harvest | Straw, roots | Grain | Stahl-Schröder, 1904 |
| | Ca | Harvest | Leaves | Grain | Lundegårdh, 1932 |
| | Ca | 4-8 weeks | Roots | Leaves, stems | Burström, 1934 |
| | Mg | Harvest | Straw | Grain | Atterberg, 1887; Truninger, 1944 |
| | Mn | 6 weeks | Roots | Tops | Burström, 1934 |
| ONION (*Allium cepa*) | | | | | |
| | B | Apr.-Sept. | Leaves | Roots | Eaton, 1944 |
| | Mn | Harvest | Outer skin of bulb | Inner part of bulb | Muckenhirn, 1936 |
| ORANGE (*Citrus aurantium*, etc) | | | | | |
| | N | ———— | Roots | Stems, leaves | Chapman & Liebig, 1940 |
| | P | July | Stems, older roots | Leaves, fine roots | Chapman & Brown, 1941 |
| | Ca | Feb. | Leaves | Stems, roots | Reed & Haas, 1923 |
| | S | ———— | Leaves | Stems, rootlets | Haas, 1936b |
| | S | July | Stems, older roots | Leaves, fine roots | Chapman & Brown, 1941a |
| | B | Various | Leaves | Fruit | Morris, 1938 |
| PEA (*Pisum sativum*) | | | | | |
| | P | July | Leaves and stems | Fruit | Opitz, 1944 |
| | K | Harvest | Foliage | Seeds | Maschhaupt, 1934 |
| | B | Harvest | Foliage | Fruit walls, seeds | Truninger, 1944a |
| PEACH (*Prunus persica*) | | | | | |
| | N | June-Aug. | Fruit flesh | Endocarp, seeds | Lott, 1942 |
| | B | Nov. | Roots | Leaves, stems | Eaton, 1944 |
| PEANUT (*Arachis hypogaea*) | | | | | |
| | P | Harvest | Fruit walls | Seeds | Burkhart & Collins, 1942 |
| | K | Harvest | Fruit walls | Seeds | Burkhart & Collins, 1942; Collins & Morris, 1942 |
| | Ca | Harvest | Fruit walls | Seeds | Collins & Morris, 1942 |
| | Mg | Harvest | Fruit walls | Seeds | Collins & Morris, 1942; Burkhart & Collins, 1942 |
| PEAR (*Pyrus communis*) | | | | | |
| | N | Sept.-Oct. | Leaves | Stems, roots, fruit | Wagner, 1931 |
| | K | Sept.-Oct. | Leaves, twigs | Older stems, roots, fruit | Wagner, 1931 |
| | B | ———— | Leaves, twig bark | Twig wood | Eaton *et al.*, 1941 |
| PECAN (*Carya pecan*) | | | | | |
| | Zn | Aug. | Petioles, stems | Leaf laminae | Finch & Kinnison, 1936 |
| PERSIMMON (*Diospyros Kaki*) | | | | | |
| | B | Nov. | Leaves | Stems, roots | Eaton, 1944 |
| PINEAPPLE (*Ananas sativus*) | | | | | |
| | B | ———— | Leaf tips | Other organs | Dean & Tanada, 1943 |
| | Zn | ———— | Stem growing point | Other organs | Lyman & Dean, 1942; Dean & Tanada, 1943 |
| PLUM (*Prunus domestica*) | | | | | |
| | K | ———— | Leaves | Fruit pulp | Lilleland, 1931; Wallace, 1931; Wallace & Proebsting, 1933 |
| | B | Oct. | Stems | Leaves | Eaton, F. M., 1935; Eaton *et al.*, 1941 |
| | Cu | Late midsummer | Leaves | Stems | Anderssen, 1932 |

| Plant | Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference. |
|---|---|---|---|---|---|
| POTATO (*Solanum tuberosum*) | | | | | |
| | N | 5-13 weeks from planting | Petioles, stems, tubers, roots | Leaf laminae | Lorenz, 1944 |
| | N | 9-13 weeks from planting | Petioles, stems, tubers, roots | Leaf laminae | Lorenz, 1944a |
| | P | 5-13 weeks from planting | Roots | Leaf laminae, petioles, stems, tubers | Lorenz, 1944 |
| | K | Harvest | Tops | Tubers | Metz, 1923 |
| | Mg | ———— | Leaves | Tubers | Garner *et al.*, 1930 |
| | Mg | ———— | Lower leaves | Upper leaves | Carolus, 1934 |
| | B | May | Leaves | Tubers | Eaton, 1944 |
| | Mn | Harvest | Outer skin of tubers | Inner part of tubers | Muckenhirn, 1936 |
| | Cu | Jan.-Mar. (C) | Leaves | Tubers | Teakle, Morgan & Turton, 1941 |
| RADISH (*Raphanus sativus*) | | | | | |
| | B | 62 days | Leaves | Roots | N.J. agric Exp. Sta., 1939 |
| | B | ———— | Tops | Roots | Muhr, 1942; Tanada & Dean, 1942 |
| | B | Various | Leaves | Roots | Eaton, 1944 |
| RED CLOVER (*Trifolium pratense*) | | | | | |
| | Ca | ———— | Tops | Roots | DeTurk, in Hambidge, 1941 |
| | B | Harvest | Straw | Seeds | Truninger, 1944a |
| RED CURRANT (*Ribes sativum*) | | | | | |
| | K | July | Leaves | Stems | Wallace, 1929b; Wallace & Proebsting, 1933 |
| RED PEPPER (*Capsicum frutescens*) | | | | | |
| | Mg | ———— | Leaves | Fruit | Carolus, 1935 |
| | B | Oct. | Leaves | Fruit. | Eaton, 1944 |
| RICE (*Oryza sativa*) | | | | | |
| | S | Dec.-Jan. | Straw | Grain | Sen, 1938a; Aiyar, 1945 |
| | Cu | ———— | Grain | Straw, roots | Tokuoka & Dyo, 1938 |
| RUTABAGA (*Brassica* sp) | | | | | |
| | Ca | Harvest | Tops | Roots | Beaumont & Snell, 1935 |
| | Mg | Harvest | Tops | Roots | Beaumont & Snell, 1935 |
| RYE (*Secale cereale*) | | | | | |
| | P | Harvest | Straw | Grain | Wagner, 1915; Alway *et al.*, 1926 |
| | K | Harvest | Straw | Grain | Wagner, 1915 |
| SNAP BEAN (*Phaseolus vulgaris*) [*see also* French Bean] | | | | | |
| | Mg | ———— | Leaflets | Petioles, stems, fruit | Carolus, 1935 |
| SOYBEAN (*Glycine soja*) | | | | | |
| | Fe | 30 days from germination | Roots | Leaves | Somers & Shive, 1942 |
| | Mn | 30 days from germination | Roots | Leaves | Somers & Shive, 1942 |
| STRAWBERRY (*Fragaria chiloensis*) | | | | | |
| | P | Fruiting | Leaves | Fruit | Lineberry & Burkhart, 1943 |
| | P | June | Crown leaves (H) | Runner leaves (H) | Lineberry *et al.*, 1944 |

| Plant Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference |
|---|---|---|---|---|
| SUGAR BEET (*Beta vulgaris*) | | | | |
| N | Harvest | Roots | Leaves | Wagner, 1915 |
| P | Sept. | Stems (D) | Leaves (D) | McCool & Weldon, 1928 |
| K | Harvest | Foliage | Roots | Münter, 1920 |
| K | Sept. | Stems (D) | Leaves (D) | McCool & Weldon, 1928 |
| K | Harvest | Older leaves | Younger leaves, roots | van Schreven, 1937 |
| Ca | Harvest | Roots | Leaves, crown | Hirst & Greaves, 1944 |
| Na | Harvest | Leaves | Roots | van Schreven, 1937 |
| B | ———— | Leaves | Roots | Brandenburg, 1939 |
| B | ———— | Tops | Roots | Muhr, 1942 |
| B | Various | Leaf laminae | Roots | Eaton, 1944 |
| B | Harvest | Leaves | Roots | Truninger, 1944a |
| Mn | Harvest | Leaves | Roots | de Haan, 1937; Marsh & Powers, 1945 |
| SUGAR CANE (*Saccharum officinarum*) | | | | |
| N | 10-18 months after planting | Lower stems | Leaves, upper stems | Das & Cornelison, 1936 |
| N | ———— | Lower stems | Leaves, upper stems | Clements *et al.*, 1941 |
| P | ———— | Lower stems | Leaves, upper stems | Clements *et al.*, 1941 |
| K | ———— | Older leaves, older stems | Younger leaves, younger stems | Clements *et al*, 1941 |
| B | ———— | Leaf laminae | Leaf sheaths, stems | Tanada & Dean, 1942 |
| SUNFLOWER (*Helianthus annuus*) | | | | |
| Fe | ———— | Younger leaves | Older leaves | Glenister, 1944 |
| B | Various | Leaves | Stems, roots | Scofield *et al.*, 1940 |
| SWEET POTATO (*Ipomaea batatas*) | | | | |
| Mg | ———— | Leaves | Tubers | Garner *et al.* 1930 |
| B | Oct. | Tops | Roots | Eaton, 1944 |
| TEA (*Thea sinensis*) | | | | |
| P | May | Older leaves | Younger leaves, stems | de Haan, 1941 |
| K | May | Stems | Leaves | de Haan, 1941 |
| Ca | May | Stems | Leaves | de Haan, 1941 |
| TOBACCO (*Nicotiana tabacum*) | | | | |
| K | Near maturity | Younger leaves (F)<br>Older leaves (G) | Older leaves (F)<br>Younger leaves (G) | Drake & Scarseth, 1940 |
| K | After curing | Older leaves | Younger leaves | Gribbins *et al.*, 1941 |
| Mg | ———— | Older leaves | Younger leaves, stems | Garner *et al.*, 1930 |
| TOMATO (*Lycopersicum esculentum*) | | | | |
| N | Blossoming, fruiting | Stems | Leaves | Bartholomew *et al.*, 1933 |
| N | Sept. | Leaves, stems | Roots, fruit | Raleigh & Chucka, 1944 |
| P | Aug. | Lower stems | Upper stems, leaves, fruit, roots | Carolus, 1943a |
| P | Sept. | Roots | Leaves, stems, fruit | Raleigh & Chucka, 1944 |
| K | April-May | Stems | Leaves | Wall, 1939 |
| K | April-May | Stems | Leaves, fruit | Wall, 1940a, 1940b |
| K | Sept. | Leaves, stems, roots | Fruit | Raleigh & Chucka, 1944 |
| K | End of season | Lower leaves | Upper leaves | Clarke, 1944 |
| Ca | Sept. | Leaves, stems, roots | Fruit | Raleigh & Chucka, 1944 |
| Mg | Sept. | Leaves, stems | Roots, fruit | Raleigh & Chucka, 1944 |
| Fe | Various | Upper leaflets, fruit | Lower leaflets | Lyon *et al.*, 1943 |
| B | July-Aug. | Leaves | Fruit | Eaton, 1944 |
| Mn | Various | Lower leaflets | Upper leaflets, fruit | Lyon *et al.*, 1943 |
| Zn | Various | Fruit | Leaflets | Lyon *et al.*, 1943 |
| Mo | Various | Lower leaflets | Upper leaflets, fruit | Lyon *et al.*, 1943 |

| Plant | Element | Date or stage of development | (A) (*see* Notes) | (B) (*see* Notes) | Reference. |
|---|---|---|---|---|---|
| TURNIP (*Brassica rapa*) | | | | | |
| | N | Harvest | Roots | Leaves | Wagner, 1915 |
| | K | Harvest | Roots | Leaves | Wagner, 1915 |
| | B | May | Leaves | Roots | Eaton, 1944 |
| WHEAT (*Triticum vulgare*) | | | | | |
| | P | Harvest | Straw | Grain | Hall, 1905; Wagner, 1915; Maschhaupt, 1921 |
| | P | Harvest | Grain | Straw | Ames, 1910 |
| | K | Harvest | Straw | Grain | Helmkampf, 1892; Hall, 1905; Ames, 1910; Wagner, 1915 |

**NOTES**

A. Organ(s) whose percentage nutrient content varied more markedly with increase in nutrient supply.
B. Organ(s) whose percentage nutrient content varied less markedly with increase in nutrient supply.
C. In Southern Hemisphere.
D. Nutrients determined in expressed sap.
E. Percentage content of inorganic phosphate determined.
F. At low level of potassium supply.
G. At high level of potassium supply.
H. Nutrients determined in hot water extract.

It is clear from Table IV that, in the majority of cases for which data are available, the proportional increase in internal concentration of a nutrient with increase in its supply is greater in the leaves than in other organs. Thus, so far as it goes, this evidence supports the broad generalization put forward by Thomas and Mack (1939) and by Wallace (1943) that leaf analysis is to be preferred in diagnostic work.

Those investigators, whose methods involve the analysis of extracts of the plant tissue or sap considered to contain only unelaborated nutrients, have often preferred to sample organs with a large proportion of conducting tissue—stems, petioles or midribs. The few data in Table IV bearing on this point (McCool and Weldon, 1928; Neller, 1935) do, indeed, support this practice. Thornton (1932) stated that the inorganic phosphate content of the translocation and storage tissues was a more sensitive index of phosphorus nutrition than that of the leaves. Emmert (1942a) found that the lower petioles of tomatoes, extracted with 2% acetic acid, were preferable to other organs for the indication of current nutrient supply, because temporary changes in environmental conditions affecting growth rate had less effect on the composition of the extract of these petioles than on that of other organs. An additional reason for choosing organs with little pigmentation for extraction may be that the presence of pigments, tannins, etc. may affect the accuracy and ease of carrying out colorimetric tests (Nicholas and Jones, 1945; A. W. Greenhill, private communication).

It must be remembered that in choosing a type of sample for diagnostic purposes it may be necessary in practice to use the same sample for determination of several nutrients. In other words, a compromise must be effected, and a sample giving reasonable indications of the status of all nutrients under study selected rather than a type of sample most appropriate for one nutrient but unsatisfactory for others.

The actual sample types chosen by certain investigators may be seen in Tables II, XII and XV; types used by other investigators who have carried out systematic work in this field but who have not proposed any numerical limiting values or ratios are shewn in Table V unless mentioned elsewhere in this section.

## Table V

**Material used or recommended for diagnostic purposes in investigations other than those mentioned in Tables II, XII and XV.**

| Plant | Elements | Time or stage of development | Part sampled | Reference |
|---|---|---|---|---|
| APPLE (*Pyrus malus*, etc.) [*see also* Deciduous fruits] | | | | |
| | General | ——— | Middle shoot leaves | Boynton & Compton, 1944; Boynton, 1945 |
| | General | July-Sept. | Petioles near base of leader growth | Nicholas & Jones, 1945 |
| | General | ——— | Terminal 5″ of twig | Davidson, in Hambidge, 1941 |
| | N | ——— | Middle shoot leaves | Baker, 1936; Magness *et al.*, 1940; Smock & Boynton, 1944 |
| | K | Various | Middle shoot leaves | Baker, 1941; Boynton *et al.*, 1941; Boynton & Cain, 1942 |
| | K | ——— | Leaves | Reuther, 1941 |
| | K | Various | Petioles | Potter & Percival, 1938 |
| | Mg | Jan.-Feb. | Lower leader leaves | Kidson *et al.*, 1943 |
| | Mg. | Various | Leaves | Southwick & Shaw, 1944; Southwick & Smith, 1945 |
| BARLEY (*Hordeum vulgare*) [*see* Small Grains] | | | | |
| BEET (*Beta vulgaris*) | | [*see also* Sugar beet] | | |
| | K | ——— | Roots | Gilbert, 1926 |
| | B | ——— | Leaves | Berger & Truog, 1940 |
| CABBAGE (*Brassica oleracea*) | | | | |
| | N | ——— | Midribs | Gilbert, 1926 |
| | N, P | ——— | Midribs | Emmert, 1935b |
| | P | Beginning of head formation | Lower part of stem | Thornton, 1932 |
| CACAO (*Theobroma cacao*) | | | | |
| | General | Various | Leaves from most recent growth flush | McDonald, 1933 |
| CAULIFLOWER (*Brassica oleracea*) | | | | |
| | General | Oct. | Midrib of first upright leaf. | Nicholas & Jones, 1945. |
| CELERY (*Apium graveolens*) | | | | |
| | K | ——— | Stems | Gilbert, 1926 |
| CITRUS (*Citrus* spp.) | | [*see also* Grapefruit, Orange] | | |
| | General | June-July* | Leaves from fruit stalk against fruit | Bathurst, 1943 |
| | General | May-July* | Leaves from growth flush at time of setting main crop | Bathurst, 1944a |
| | N | ——— | Mature leaves | Hilgeman *et al.*, 1940 |
| | Mg | April | Spring flush foliage | Fudge, 1942a |
| CLOVER (*Trifolium* spp.) | | [*see also* Legumes, Subterranean Clover] | | |
| | P | ——— | Growing tips of main stems | Thornton *et al.*, 1934 |
| | K | ——— | Main stems | Thornton *et al.*, 1934 |
| DECIDUOUS FRUITS [*see also* Apple, Peach, Plum] | | | | |
| | General | ——— | Leaves from lower part of current season's growth. | McCollam, 1944 |

*In Southern Hemisphere.

| Plant | Element | Time or stage of development | Part sampled | Reference |
|---|---|---|---|---|
| GRAPE (*Vitis vinifera*) | | | | |
| | General | ——— | Recently matured leaf some distance from tip of new cane | McCollam, 1944 |
| GRAPEFRUIT (*Citrus paradisi*) [*see also* Citrus] | | | | |
| | N | ——— | Leaves, twigs | Martin, 1940 |
| HOP (*Humulus lupulus*) | | | | |
| | General | Aug. | Petioles from mid-stem region | Nicholas & Jones, 1945 |
| LEGUMES (*see also* Clover, Lima Bean, Lucerne, Pea, Snap Bean, Soya Bean, Subterranean Clover, White Bean) | | | | |
| | K | ——— | Tips of main stems | Thornton, 1933a |
| LETTUCE (*Lactuca sativa*) | | | | |
| | N, P | Various | Older midribs | Emmert, 1934 |
| | K | ——— | Leaves | Gilbert, 1926 |
| LIMA BEAN (*Phaseolus lunatus*) [*see also* Legumes] | | | | |
| | N, P | ——— | Main stem | Emmert, 1935b |
| LUCERNE (*Medicago sativa*) [*see also* Legumes] | | | | |
| | P | Before blossom formation | Growing tips of main stems | Thornton, 1932; Thornton *et al.*, 1934 |
| | K | ——— | Main stems | Thornton *et al.*, 1934 |
| MAIZE (*Zea mays*) | | | | |
| | General | Various | Third leaf from base | Thomas, 1938b; Thomas & Mack, 1939, 1939a, 1939b, 1939c, 1939e, 1943; Thomas *et al.*, 1943 |
| | General | Various | Fourth leaf from base | Thomas *et al.*, 1944 |
| | N | ——— | Stem internodes | Gilbert, 1926 |
| | N | ——— | Bases of main stems | Thornton *et al.*, 1934 |
| | P | Between tasselling and silking | Main stems, just below tassel | Thornton, 1932; Thornton *et al.*, 1934 |
| | P | ——— | Stem tips | Gilbert, 1926 |
| | K | ——— | Base of leaf at ear node | Thornton, 1933a; Thornton *et al.*, 1934 |
| OATS (*Avena sativa*) [*see* Small Grains] | | | | |
| ONION (*Allium cepa*) | | | | |
| | General | ——— | Leaf bases | Plant *et al.*, 1945 |
| ORANGE (*Citrus aurantium*, etc.) [*see also* Citrus] | | | | |
| | General | ——— | Leaf from spring cycle of growth, just behind a small green fruit. | McCollam, 1944 |
| PEA (*Pisum sativum*) [*see also* Legumes] | | | | |
| | N, P, K | Various | Stem | Wolf, 1945 |
| PEACH (*Prunus persica*) [*see also* Deciduous fruits] | | | | |
| | General | ——— | Terminal 6″ of twig | Davidson, in Hambidge, 1941 |
| | N, P, K | Various | Leaves | Waugh & Cullinan, 1941 |
| | N, P | Dormant season | Twigs | Waltman, 1944 |
| | N, P | ——— | New shoots, growing tips | Emmert, 1935b |
| | P, K | ——— | Leaves | Lilleland, 1933 |
| | P, K | June, July | Basal leaves of current season's growth | Lilleland & Brown, 1941, 1942 |
| | K | Various | Terminal leaves | Baker, 1941 |

| Plant | Element | Time or stage of development | Part sampled | Reference |
|---|---|---|---|---|
| PINEAPPLE (*Ananas sativus*) | | | | |
| | N | Various | Leaf bases | Tam & Clark, 1943 |
| PLUM (*Prunus domestica*) [*see also* Deciduous fruits] | | | | |
| | K, Ca, Mg | Various | Leaves | Hoagland & Chandler, 1933 |
| | K | Aug.-Sept. | Middle shoot leaves | Boynton *et al.*, 1941 |
| POTATO (*Solanum tuberosum*) | | | | |
| | General | Various | 4th-11th leaves from base of primary stems | Thomas & Mack, 1938 |
| | General | July-Aug. | Petioles from mid-stem region | Nicholas & Jones, 1945 |
| | N, P, K | Early stages of tuber development | Main stem near ground | Thornton, 1932, 1933a ; Thornton, *et al.*, 1934 |
| | N, P, K | Various | 4th or 5th leaves from base of primary stems | Thomas, 1936, 1937, 1938, 1938a ; Thomas & Mack, 1939c, 1939d, 1939f |
| | N, P | ——— | Lower main stems | Emmert, 1937 |
| | P, K | ——— | Leaf nearest inflorescence | Sandrock, 1931 |
| RASPBERRY (*Rubus idaeus*) | | | | |
| | K | Autumn | Leaves | Darrow & Magness 1939 |
| RUBBER (*Hevea brasiliensis*) | | | | |
| | N, P, K | Dormancy | Largest leaf laminae of whorl | Chapman, 1941 |
| RYE (*Secale cereale*) [*see* Small Grains] | | | | |
| SMALL GRAINS [*see also* Wheat] | | | | |
| | N | ——— | Main stems | Thornton *et al.*, 1934 |
| | P | " Jointing " | Growing tips of main stems | Thornton, 1932 ; Thornton *et al.*, 1934 |
| | K | ——— | Bases of leaves near middle of main stems | Thornton, 1932a ; Thornton *et al.*, 1934 |
| SNAP BEAN (*Phaseolus vulgaris*) [*see also* Legumes] | | | | |
| | General | Various | Basal leaves | Thomas *et al.*, 1942 |
| SOYA BEAN (*Glycine soja*) [*see also* Legumes] | | | | |
| | P | ——— | Growing tips of main stems | Thornton *et al.*, 1934 |
| | K | ——— | Main stems | Thornton *et al.*, 1934 |
| SPINACH (*Spinacia oleracea*) | | | | |
| | N, P, K | ——— | Petioles | Thornton *et al.*, 1934 |
| | K | ——— | Leaves | Gilbert, 1926 |
| SUBTERRANEAN CLOVER (*Trifolium subterraneum*) [*see also* Clover, Legumes] | | | | |
| | Mo | Beginning of flowering | Leaves | Teakle, 1944 |
| SUGAR BEET (*Beta vulgaris*) [*see also* Beet] | | | | |
| | General | ——— | Leaves midway between old outer leaves and small immature ones | McCollam, 1944 |
| | General | Aug. | Midrib of first upright leaf | Nicholas & Jones, 1945 |
| | N, P, K | ——— | Petioles | Thornton, 1932 ; Thornton *et al.*, 1934 |
| | N | ——— | Petioles of central leaves | Ulrich, 1941 |
| SUGAR CANE (*Saccharum officinarum*) | | | | |
| | N, P, K | ——— | Tops | Hance, 1936 |
| | N, P, K | ——— | Punch samples from centre region of 3rd-5th leaves from apex. | Hance, 1937 |

| Plant | Element | Time or stage of development | Part sampled | Reference |
|---|---|---|---|---|
| TOBACCO (*Nicotiana tabacum*) | | | | |
| | General | Various | Leaves (various levels) | Lagatu & Maume, 1935, 1935a, 1935e, 1936c |
| | N, P, K | ——— | Base of midribs from upper part of main stems | Thornton *et al.*, 1934 |
| TOMATO (*Lycopersicum esculentum*) | | | | |
| | General | Various | Leaves (various levels) | Thomas & Mack, 1941a, 1941b ; Thomas *et al.*, 1943a |
| | General | Oct.-Dec. | Petioles from mid-stem region | Nicholas & Jones, 1945 |
| | N, P, K | ——— | Petioles from middle of main stem | Thornton *et al.*, 1934 |
| | N, P, K | Various | 5th leaf from base | Thomas & Mack, 1940, 1941, 1943a |
| | N | Various | Older petioles | Emmert, 1934, 1935b |
| | N | ——— | Leaves | Gilbert, 1926 |
| TURNIP (*Brassica rapa*) | | | | |
| | N, P, K | ——— | Petioles | Thornton *et al.*, 1934 |
| WHEAT (*Triticum vulgare*) [*see also* Small Grains] | | | | |
| | N, P, K | Earing, flowering | Tops | Maume & Dulac, 1934, 1934a, 1935, 1935a, 1936, 1936a, 1937, 1938, 1938a |
| | S | Earing, flowering | Tops | Maume & Bouat, 1937 |
| WHITE BEAN (*Phaseolus* sp.) [*see also* Legumes] | | | | |
| | P, K | ——— | Leaves | Cook, R. L., 1941 |

## PREPARATION OF MATERIAL FOR ANALYSIS

### Cleaning

The first necessity is that the external surface of the material shall be free from contamination, particularly with substances containing the elements under investigation. Where the trace elements are concerned, a very small amount of contamination may contain sufficient completely to invalidate the analytical results.

The most important sources of contamination are soil, atmospheric dust and spray materials. Soil contamination is of course most important for root samples—it has indeed often been a reason for the rejection of root samples as material for diagnostic analysis (Helmkampf, 1892 ; Stahl-Schröder, 1904)—but it may also be considerable on leaves and stems near ground level. The total content of many of the trace elements (including iron) and also of calcium in soil may be considerably higher than in plant dry matter, and hence soil contamination may result in over-estimation of the content of these elements in the plant material ; iron content of dry plant material samples has even been used as an index of soil contamination, and so also has their aluminium content (Piper, 1942a). Atmospheric dust is often similar in composition to soil, but in the vicinity of industrial works it may contain considerable quantities of other materials containing elements of interest in plant nutrition ; dust may contaminate all the aerial parts of the plant. Spray residues are an important source of contamination for the fruit, stems and leaves of crops to which sprays are normally applied. They commonly contain calcium, sulphur or copper—all of importance in plant nutrition—and may contain a wide variety of other elements. Lindner (1943) has shewn that spray may carry a considerable distance—at half a mile from the nearest point where an arsenic spray had been used, surface contamination of peach leaves with arsenic amounted to two or three times their normal arsenic content.

The removal of surface contamination from plant material is not a simple matter. Many investigators recommend washing samples with distilled water (Parbery, 1935 ; Thorne and

Wallace, 1944). This however is liable to cause losses of certain nutrients from the plant material by leaching ; this may be particularly serious for potassium—if the leaching is continued long enough, up to 99% of the total potassium in apple leaves may be lost (Mann and Wallace, 1925), and even rain will remove considerable amounts (Richards, 1932 ; van Schreven, 1938 ; Albrecht, 1943). Moreover, it is not at all certain how effective washing in distilled water may be for the removal of insoluble surface contaminants. Other workers (Boynton *et al.*, 1944 ; Goodall, 1943, 1945, 1945a ; Bathurst, 1944a ; Roach, 1944) have wiped the surface of the organs with muslin or other cloth, or with cotton wool ; this avoids the possibility of leaching, but again its effectiveness in removing contamination is open to question. So far as the author is aware, neither of these procedures has ever been tested carefully—neither the amounts removed nor the amounts remaining have been estimated. A test would be possible by artificial contamination with some material not normally present to an appreciable extent in plant tissue—but even then one could never be sure that any amount remaining had not been absorbed by the leaf, and it would be very doubtful whether results obtained could be applied to field conditions.

Lindner (1943) found that washing with water was inadequate to remove arsenic spray residues on peach leaves. Accordingly he dipped the leaves in an alcoholic solution of sodium hydroxide. This technique would probably not be generally applicable. In another investigation, mainly on pear leaves, the same investigator (Lindner and Harley, 1944) first swabbed the leaves with moist cotton and then rinsed in distilled water.

Jacobson (1945) found it necessary to rub leaves intended for iron determinations with 0.3 N hydrochloric acid, in order adequately to remove spray residues and dust.

**Drying**

When cleaned, it is generally necessary for the material to be dried. Some analytical procedures do indeed demand the use of fresh material, either directly or in the form of an extract or expressed sap (see below) ; but generally the dried plant material forms the starting point of the analyses, having the important advantage that it can be stored indefinitely if immediate analysis is inconvenient. Unless the material can be killed soon after collection, it is desirable that drying should proceed rapidly, to avoid respiratory losses. Goodall (1945b) has shewn that, in young tomato plants, these commonly lie between 0.2 and 0.5% of the dry weight per hour at moderate temperatures—that is, over a period of twenty-four hours a loss of between 5 and 10% might well take place, resulting in a corresponding increase in the apparent percentage nutrient content. This loss would of course be prevented if the temperature of the material were rapidly raised to a point at which respiration ceased. But the heat distribution in many types of oven is far from uniform, especially when they contain a large bulk of moist material, so that this condition will often not be fulfilled.

The exact temperature of drying is probably not a matter of great importance provided it is standardized ; there is little likelihood of appreciable losses of nutrients (except possibly sulphur) if the temperature does not exceed 100°C. Some interconversion of organic compounds of nutrients — particularly nitrogen, phosphorus and sulphur — may occur, but unless the diagnostic analysis is carried out only for one or other of these compounds or groups of compounds such interconversion will not affect the result. As will be shewn later, it has rarely been suggested that analysis for these organically combined fractions would be of greater diagnostic value than the total content of the same nutrient or its inorganic fractions.

It goes without saying that in the drying process the risk of contamination from the material of the oven, or of trays in which the material is placed, should be avoided. If the internal surface of the oven is composed of a metal of interest in plant nutrition as a trace element, there may be a serious risk of minute flakes falling on the samples and causing substantial errors (Piper, 1942a).

**Grinding**

It is usual to grind the dried plant material before analysis—partly for greater ease in manipulation, partly in order to secure greater uniformity in composition. Very often a mechanical mill is used for grinding, but this may lead to serious contamination with some of the elements present in smaller quantity in plant material. Hood *et al.* (1944) made a careful study of the Wiley mill (using blades), the C and N mill (beater action) and various types of ball mills ; they

found that all caused contamination with iron and copper, and the ball mills with other elements besides. If the contamination were constant, allowance could be made for it ; but in fact it was found to be erratic. Piper too (1942a) considered that any steel mill was not permissible for samples intended for iron determination—a bronze C and N mill could be used ; if copper or zinc determinations were to be made the mill should contain no brass, even in parts not coming directly into contact with the material. Drosdoff (1944), on the other hand, found only slight iron contamination from the Wiley mill. Where samples are small, they can generally be ground by hand—preferably in an agate mortar—to avoid contamination (though even small amounts of some types of material, especially cereal stems, are difficult to grind by hand) ; but when there is any considerable quantity of material, hand grinding becomes excessively laborious, and choice must be made between the types of contamination caused by the different mills. By grinding the material separately in different mills for copper and iron determinations, fully satisfactory results should be possible.

## THE ANALYSIS ITSELF

### Determination of a Nutrient other than that Deficient

The great majority of diagnostic methods involving the use of plant analysis have been based on determinations in the tissues of the element whose status is in question. An outstanding exception was the " stalk-test " method (Hoffer, 1926), extensively used with maize in America for some years. This depended upon the observation by Hoffer and Trost (1923) that under conditions of potassium deficiency accumulations of insoluble iron compounds appeared in the nodes. The test was never intended as any more than a very rough indication of the potassium status of the plants and of the soil in which they were growing, and as such was found useful in a number of investigations ; the agreement with other tests of potassium status was moderate (Eckstein and Jacob, 1929 ; Thornton, 1931 ; Krüger *et al.*, 1931 ; Stewart *et al.*, 1932 ; Pettinger and Thornton, 1934). Other investigators, however, found the test of little value (Welton *et al.*, 1926 ; Salter and Ames, 1928 ; Snell and McKibbin, 1933). Eckstein and Jacob (1929) had suggested that iron accumulation under conditions of potassium deficiency was not confined to maize, but Krüger *et al.* (1931) found the test inapplicable to oats and Neeb (1931) to sugar cane. As direct rapid tissue tests for potassium were developed, this method was gradually abandoned. Among other instances where the concentration in the plant of some substance other than that deficient has been suggested as an index of the deficiency may be mentioned Roach's (1940, 1943) use of calcium content to indicate probable deficiencies of iron and other trace elements, the suggestion from Trinidad (Emp. Cott. Gr. Corp., 1942) that the sugar content of cotton leaves might provide a means of determining their potassium status, and Leeper's (1941) observation that under conditions of manganese deficiency oats and *Phalaris minor* accumulate in their stems large amounts of nitrate.

### Determination of the Deficient Nutrient

Where the nutrient whose status is under investigation is itself to be determined in the plant material, the question needs to be raised whether the determination shall be performed on the whole plant material, or upon some extract of it. Since, unless extraction is complete, an extraction technique removes certain chemical fractions preferentially, this problem is closely linked with the question of whether particular chemical fractions of the nutrient should be investigated.

#### *Analysis for Particular Chemical Fractions*

It has frequently been claimed that those fractions of the nutrients within the plant which have not yet been built up into its tissues—the " unelaborated" fractions—provide an index of the balance between current uptake of these nutrients and their utilization by the meristems (Carolus, 1938a, Ulrich, 1944)—a better index of current nutrition than the total nutrient content, since the elaborated fractions present mainly in the insoluble part of the plant material tend to form a relatively constant proportion of it (Emmert, 1942). It may be pointed out that the unelaborated fractions of nutrients in many cases do not themselves constitute the materials directly necessary for meristematic activity, and that consequently no direct connection between

the rate of growth of the plant and the concentration of unelaborated nutrients within it can be assumed. There is, however, a not inconsiderable body of evidence to show that the concentrations of the unelaborated fractions of nutrients in the plant indicate their status more clearly than the total concentration of the same nutrients.

NITROGEN. Most of the evidence as to the relative value of elaborated and unelaborated nutrient fractions in plant material as diagnostic indices relates to nitrogen, and particularly to nitrate determinations. Ulrich (1942a, 1942b, 1943), for instance, compared the effect of sulphate of ammonia on the nitrate-nitrogen, total soluble nitrogen, and insoluble nitrogen content of grape petioles and leaf-blades ; the proportional effect on the nitrate content of the petioles was larger than on any of the other fractions in petioles or blades, and for the earlier samples the significance of the effect was also greater. His observations (1943, 1943a) on the effect of four levels of nitrogen supply on the nitrogen content of sugar beet are rather more equivocal ; he concludes that " the nitrate content of the outside petioles . . . . for June 1 indicated the nitrogen status of the plants better than any other nitrogen fraction," but in fact at that date the significance of the differences observed in the total soluble nitrogen content of the same organs was rather greater than that for their nitrate content.

Most other investigations on the subject relate only to the proportional changes in the various nitrogen fractions in the plant with different nitrogen fertilizer treatment. Cook (1930) found the changes in nitrate content of the sap of oat plants following application of nitrogenous fertilizers were proportionally much greater in most cases than those in the total nitrogen content of the same tissues. Emmert (1931), in experiments in which tomatoes and lettuces were grown in soils varying in reaction, found that the nitrate concentration in the leaves gave better indication of soil nutrient relations than the total nitrogen content, especially in tomatoes. Investigations in Rhode Island (R.I. agric. Exp. Sta., 1933, 1934) showed that in beet and celery the nitrate content of the juice consistently reflected the nitrogen supply level, but that the ammonia content did not. Garner and his collaborators (Garner *et al.*, 1934) analysed tobacco leaves from plants receiving different levels of nitrogen supply for six nitrogen fractions, and found that the nitrate content shewed much greater proportional differences than any other fraction until the flowering stage was reached ; in cured leaves (Garner, 1939) the effect of nitrogen supply on nitrate content was less regular than the effect on other nitrogen fractions. Lowry *et al.* (1936), studying the exuded sap of maize in a manurial trial, found that the differences in nitrate content as a result of application of sulphate of ammonia were both more marked and rather more consistent than those in total nitrogen content. Richards and Templeman (1936), in a careful study of the nitrogen metabolism of barley leaves of different ages, found the proportional difference in nitrate content with different nitrogen supply almost invariably greater than in any other of the five nitrogen fractions studied. In cotton plants grown in sand culture and analysed at flowering, Wadleigh (1938) found that nitrogen supply affected the concentration of nitrogen fractions other than nitrate very little though the percentage of nitrate varied greatly with the treatment.

Other workers, on the contrary, have found little reason to prefer the content of nitrate nitrogen as a diagnostic index to that of other fractions. Carolus and his collaborators (Carolus, 1938 ; Carolus *et al.*, 1938) found that in the 2% acetic acid extract of stems or petioles of potato and cabbage, the nitrate nitrogen and soluble nitrogen content reflected the nitrogen nutrition in very similar fashion. The data of Lorenz and Minges (1942) shewed that, in the 2% acetic acid extract of the midribs of outer leaves from lettuce plants subjected to various nutritional treatments, the proportional differences in nitrate content were only slightly greater than those in total soluble nitrogen.

A few investigators have not determined nitrate nitrogen, but have compared only the soluble and insoluble nitrogen content, or that of protein and non-protein nitrogen. Petrie (1937), for instance, found that in wheat and Sudan grass the proportional increase in soluble nitrogen content with increased nitrogen supply was more marked than that in insoluble nitrogen —at least in the earlier stages of growth ; Brown's (1945) data for peach shoots shew the same ; Vinall and Wilkins (1936) found changes in non-protein nitrogen in bluegrass more marked than those in protein nitrogen. The Trinidad workers (Phillis and Mason, 1939 ; Emp. Cott. Gr.

Corp., 1942 ; Mason and Phillis, 1943) considered that nitrogen deficiency should be judged by the concentration of crystalloid rather than protein nitrogen in the leaf of cotton, and shewed that the former varied much more markedly with nitrogen supply than the latter. In his careful study of the nitrogen nutrition of the cotton plant, Wadleigh (1944) concluded that the soluble organic nitrogen content of the main roots was one of the better indices of potential production.

Although much of this evidence supports the view that the content of soluble nitrogen fractions and particularly of nitrate varies more markedly with the changing nutritional conditions than that of the more fully elaborated fractions, there seems to be none demonstrating conclusively that the former provides a better index to expected yield increments with nitrogenous fertilizers. In fact, few data enabling a relationship between yield increments and the content of different nitrogen fractions to be computed appear to be available. Nevertheless, in spite of the paucity of the evidence, many investigators in the field of analytical diagnosis besides those mentioned above have chosen to determine nitrate-nitrogen rather than total nitrogen in their material ; the Purdue University system of tests (pp. 42), for instance, includes one for nitrate which was also adopted by Wark (1938, 1939) ; the Rhode Island system of tests (Gilbert, 1926) involved determination of nitrate-nitrogen only ; MacGillivray *et al.* (1930) used microchemical tests for nitrate in tomato petioles. Pettinger (Pettinger, 1931 ; Pettinger and Thornton, 1934) determined nitrate in the expressed sap of maize, and Pierre and Pohlman (1933) in the exuded sap of various grasses ; Poehlman (1935) used nitrate tests on the expressed sap of soya beans, Hester (1941) on tomato stems extracted by a sodium acetate buffer solution, Nightingale (1942, 1942a) on pineapple leaf bases, Brown (1943) on a water extract of sugar beet petioles and Harrington (1944) on snap bean stems and spinach petioles ; Bray (1945) has recently described a rapid test for nitrate in plant tissue. Emmert (1935b) considered that nitrate determinations could be carried out on petioles or succulent stems, but that on other types of material, where organic compounds interfering with the nitrate test were likely to be present in greater amount, total soluble nitrogen should be determined instead. In many instances, it seems likely that nitrate determinations have been preferred because they are so easily carried out by colorimetric methods, usually involving the use of phenoldisulphonic acid.

Phosphorus. Much less work than in the case of nitrogen has been done on the various chemical forms in which phosphorus and sulphur occur in the plant tissues and on the relation of the concentrations of these fractions to the nutrition of the plant. Mather (1929) studied the effect of different levels of phosphorus nutrition on the content of inorganic and organic phosphorus in several species of forage plants and cereals ; in general, the content of organic phosphorus was unaffected by phosphorus supply, except at the highest levels, while that of inorganic phosphorus increased regularly in step with the treatment. Thornton (1932) suggested that the content of inorganic phosphorus should be a more sensitive index than total phosphorus because it is in that form that plants well supplied with phosphorus accumulate the excess of absorption over utilization. Pfützer and Roth (1942) found that the effect of increased phosphorus supply on the content of phosphatide-phosphorus in spinach, rape and barley was less marked than that on the total phosphorus content—indicating that other fractions were more affected by the treatments than the phosphatide fraction. The Trinidad workers (Phillis and Mason, 1939 ; Mason and Phillis, 1943), studying cotton plants growing at different levels of phosphorus supply, found that the content of soluble phosphorus in the plants increased much more with the level of supply than that of the insoluble fractions.

Many investigators have confined their phosphorus analyses to phosphate ; this is true of most workers using sap or extracts of the material (Purdue University—see p. 42 ; Gilbert, 1926 ; Gilbert *et al.*, 1927 ; Pettinger, 1931 ; Emmert, 1932, 1936 ; Thornton, 1932 ; Thornton *et al*, 1934 ; Pierre and Pohlman, 1933 ; Carolus, 1936, 1938 ; Carolus *et al.*, 1938 ; Hester, 1941 ; Brown, 1941)—Neller (1935) shewed that almost the whole of the phosphorus in sap of sugar cane, sorghum and buckwheat was inorganic—and also applies to Chapman and his collaborators (Chapman, 1935 ; Chapman *et al.*, 1940) and to Ulrich (1944).

Sulphur. Peterson (1914) analysed plants of rape, radish and clover which had and had not received sulphate fertilizer for volatile sulphur, sulphate, other soluble sulphur, and the insoluble

fraction of the element, and found that the treatment affected the sulphate content of all three species far more markedly than the other fractions—in fact the content of insoluble sulphur in rape and clover was hardly affected by the treatments. Shedd (1917) found that almost the whole of the increase in the sulphur content of clover and lucerne as a result of treatment with elemental sulphur was in the sulphate fraction. In the soybean, S. V. Eaton (1935) found that the content of organic sulphur in plants suffering from sulphur deficiency differed little from that of normal plants, but the sulphate content was considerably lower. Johnson *et al.* (1943) found that the effect of gypsum application on lucerne was to increase its sulphate content, while the content of reduced sulphur remained almost unchanged. Aiyar (1945) found no sulphate in rice plants suffering from sulphur deficiency.

Other Elements. The question of fractionation hardly arises in the same way in relation to the other nutrients, for little is known of the chemical forms in which they occur in plant tissues. Thorne and Wallace (1944) made an attempt to distinguish between ferrous and ferric iron in green and chlorotic leaves of fruit trees, and found the differences in the former in acetic acid or formic acid extract to be greater, if care was taken to exclude air.

*Extraction Methods.*

The more important extraction methods which have been used for routine diagnostic purposes are :—

Expressed Sap. The expressed sap of the tissues studied has often been used for diagnostic purposes. Gilbert and his collaborators (Gilbert and Hardin, 1927 ; Gilbert *et al.*, 1927) proposed the analysis of sap from a wide range of crop plants for the three major nutrients for diagnostic purposes, the sap being obtained by grinding fresh material and straining through fine mesh silk (Gilbert, 1926) ; McCool and Weldon (1928) suggested a similar method, using sap extracted under a pressure of one ton, for phosphorus and potassium. Fonder (1929) investigated the calcium and magnesium content of the sap of bean plants grown on different soils, and Cook (1930) the nitrate content of the sap of cereals. Pettinger (1931 ; Pettinger and Thornton, 1934) used the composition of the sap of maize as a method of diagnosis of deficiencies of the three principal nutrients, and found the results to be closely related to the treatments the plants had received ; he also (1932) studied the effect of fertilizer treatment on the chlorine content of the sap. Halais (1933) and Craig (1934, 1934a) found that the phosphorus content of juice of sugar cane reflected the incidence of phosphorus deficiency and probable responses to phosphatic fertilizer treatment better than soil analysis ; they also reported that only where applications of phosphate fertilizer increased the yield was any increase in the phosphate content of the sap to be observed. Neller (1935) used sap analysis in investigations of the phosphorus nutrition of sorghum, buckwheat, sugarcane, maize and rape. Poehlman (1935) analysed the sap of soybeans for nitrate, phosphorus and potassium under various nutritional conditions, and concluded that it was not possible, as Pettinger had done, to fix critical levels for the nutrient percentages in the sap. Carolus (1936, 1937) on the other hand, working with potatoes, claimed to be able to lay down limiting values (see Table XII) for the five principal nutrients in the sap expressed from the stem, and found a similar technique valuable for other vegetable crops. Borden (1942, 1944), in an attempt to find a suitable index of the nitrogen nutrition of sugar cane, determined the nitrogen content of the crusher juice at different stages of growth, and found it related to the response to nitrogenous fertilizers applied at the time of sampling ; he had earlier (1936a) found that the phosphorus and potassium content of the crusher juice was related to the supply of these elements in the soil, and to the yield. In connection with work involving the analysis of expressed sap, it should be remembered that it has sometimes been reported that sap composition may be considerably affected by variations in the pressure used to obtain it (McCool and Millar, 1917 ; Knudson and Ginsberg, 1920 ; Fonder, 1929a), and even by differences in the rate of attaining the same final pressure (Gassner and Goeze, 1932), unless the material has first been killed. According to Phillis and Mason (1937), differences in composition of sap expressed from living material with varying pressure are probably to be ascribed to uncontrolled shearing strains, which are difficult to avoid in practice.

Most investigators using expressed sap do not appear to have compared the value of the

sap composition as a diagnostic index with that of the whole plant material from which it was expressed. Cook (1930) found the differences in the nitrate content of cereal sap with varying treatment much more marked than those in the total nitrogen content of the plant. Carolus (1936, 1937) also claimed to have found that the sap analyses represented the nutritional state of the plant better and shewed more marked differences than the analyses of the whole material, which he also carried out. Craig (1939a) found that the sap of sugar cane reflected differences in phosphorus nutrition much more markedly than the total phosphorus content of the leaves, but regarded the former as a less satisfactory diagnostic index because it was subject to very large varietal differences. Phillis and Mason (1940) found that the proportion of " adsorbed" (i.e., not sap-soluble) potassium in the cotton plants with which they were working increased with potassium supply, which suggests that the sap concentration would not be the most satisfaetory index of nutritional status.

The results of Marsh and Shive (1941) on boron nutrition of maize indicate that, since in this plant a large proportion of the boron present can be expressed with the sap, differences in boron content of the sap are little more marked than those in total boron content ; Eaton (1944) found that the proportion of the total boron in many plant species present in the expressed sap varied little under very diverse conditions of boron supply. On the other hand, Fudge's (1943) results with grapefruit indicate that, while at low boron supply levels the boron content of the sap remains almost constant in spite of an increase in the total boron present in the tissue, at toxic levels the concentration in the sap increases much more markedly than the total boron ; working with squash leaves, Smith (1944) found that the boron content of sap obtained by gentle pressure decreased more markedly under boron deficiency than any other boron fraction studied.

It has been suggested (Somers and Shive, 1942) that the iron and manganese present in the sap represent the " active " fractions of these elements, but this is contested by Arnon (1943), and does not seem in accord with some of the experimental evidence mentioned below. The data of Somers and Shive in fact suggest that symptoms of manganese deficiency or toxicity are reflected more markedly in the manganese content of the press cake than in that of the sap.

Extraction by Water. Extraction with cold or hot water has frequently been used as a method of preparing diagnostic samples of plant material for analysis. Nightingale has shewn (Nightingale, 1937 ; Nightingale *et al.*, 1931) that in plants suffering from calcium deficiency, unlike others adequately supplied with this element, almost the whole of the calcium present is insoluble in water. Marsh (1942) found the soluble calcium content of tobacco, bean, maize and oats to vary much more widely with calcium supply than the insoluble fraction, and the same held for boron. Haas's investigations of the water-soluble and insoluble boron content of avocado leaves (1943), of the tops and roots of date palms (1944) and of citrus leaves (1945) confirm this finding. The evidence already cited supporting the determination of nitrate, phosphate or sulphate concentration rather than the total content of nitrogen, phosphorus or sulphur will also indicate the use of aqueous extracts.

Burkhart and his colleagues (Burkhart, 1941, 1942 ; Burkhart and Page, 1941 ; Collins *et al.*, 1941 ; Page and Burkhart, 1941 ; Burkhart and Collins, 1942 ; Lineberry *et al.*, 1944) have used extraction of the fresh material with boiling water as a diagnostic method for peanut, cotton, and strawberry, the extract being analysed for the six principal nutrients. In many of their investigations on fertilizer trials, a tolerably close relationship was found between the analytical results and the fertilizer responses observed. This technique was compared with analysis of the whole mineral content of the plant material in relation to the reduction in internal concentration of calcium and magnesium by potassium-containing fertilizers (Burkhart, 1941) ; this reduction was more evident in the water extract of the lower leaves than in the total content of these elements in either the leaves or the whole plant. In strawberries, on the other hand (Lineberry *et al.*, 1944), the phosphorus content of hot water extract and of whole leaf material shewed similar differences with phosphate fertilizer treatment.

Brown (1943) used water extracts of petioles for the determination of the nitrate and phosphate status of sugar beet. Brickley (1943), too, used aqueous extracts of leaves of potato and pea for potassium determinations.

With water, as with other extracting media, it is important to keep the conditions under

which extraction takes place constant. For instance, Scarseth (1943) reported that drying of plant material altered the proportion of the potassium in it which was soluble in water.

Extraction by 2% Acetic Acid. The use of this extracting fluid for plant material appears to have been introduced by Emmert (1932, 1934, 1935). He carried out tests on the extracts for nitrate, phosphate and potassium, and used the method on many species, principally vegetable crops. Carolus, too (1938, 1938a), used 2% acetic acid as a routine method of extraction of stems and petioles for diagnostic purposes ; his analyses generally included calcium and magnesium, as well as the elements studied by Emmert. Both these investigators appear to have obtained very satisfactory practical results by this technique. Hill and Johnston (1940), later adopted it in an investigation of magnesium deficiency of apples, R. L. Cook, (1941) for the study of potassium deficiency in white bean, Lorenz and Minges (1942) in work on lettuce nutrition and Ulrich (1944a) for analyses of clover petioles.

The results of Carolus (1938a) indicate that—at least as far as the metallic nutrients are concerned—the proportionate changes in their concentration in the acetic acid extract are similar to those in the whole plant material. Ulrich (1942b), however, claimed that the phosphate content of the acetic extract provided a better index of phosphorus nutrition than the total phosphorus content of the material, while the results of Lorenz (1944) showed that the differences in nutrient concentrations in the acetic acid extracts of potato petioles with nutrient supply were more marked than those in total nutrient content.

Thorne and Wallace (1944) found that more iron was extracted by acetic acid from green leaves than from others suffering from iron chlorosis.

Extraction by Sodium Acetate Buffer Solution. In 1935 Morgan proposed the use of a mixed acetic acid-sodium acetate solution buffered at pH 4.8 for the extraction of nutrients from both soils and plant material. This method was adopted by Walsh and other workers in Éire (Walsh, 1942 ; Walsh and Clarke, 1942) and applied with some success to practical problems arising in advisory work. A similar solution has been used (Davidson and Blake, 1938 ; Davidson, in Hambidge, 1941) for extraction of peach shoots in nutritional experiments, for apple petioles (Potter and Percival, 1938), by Wolf (1942) on stems of lima beans and by Plant *et al.* (1945) on petioles of various crop plants.

The tests described by Hester (1941) and Wolf (1943) also involved the use of an acetate buffer solution, extraction taking place in a special apparatus in which the fresh plant material was mechanically disintegrated (Hester, 1940). Greenhill (1945) found that the time of extraction with Morgan's solution was an important factor, since the rate of extraction of potassium shewed little slackening after two hours, and that of phosphorus after three hours. The phosphorus content of extracts of barley stems by this solution reflected the manurial treatment which the plants had received less well than that of normal hydrochloric acid extracts.

Extraction by Hydrochloric Acid. In his method of triple analysis, Lundegårdh (1939, 1941) extracted dry leaf material for spectroscopic analysis with dilute hydrochloric acid ; this technique has since been adopted by Hale (private communication). Lundegårdh (1941) claimed that the whole of the metallic elements included in the spectrographic analysis were dissolved by N hydrochloric acid ; Goodall's (unpublished) determinations shewed this to be substantially true, though some 5% of the total calcium present remained in the residue. Greenhill (1945) found that extraction of fresh material with normal hydrochloric acid took at least two hours to reach completion.

Oserkowsky (1933), Thorne and Wallace (1944) and Jacobson (1945) found that the amount of iron contained in an extract of leaf material by N hydrochloric acid was related to the incidence of iron chlorosis ; as already indicated, however, Somers and Shive (1942) found the difference between the amounts of iron extractable by 0.1 N and 0.5 N hydrochloric acid a better index in lime-induced chlorosis. According to Liebich (1941) the proportion of iron in spinach leaves soluble in centinormal hydrochloric acid is low under conditions of iron deficiency, which suggests that this fraction would be a better index of iron status than the less soluble portion. The methods of Plant *et al.* (1945) include the use of concentrated hydrochloric acid for the extraction of iron and zinc.

Extraction by 1% Sulphuric Acid. Emmert (1931) used this extractant in his investigations of the phosphorus nutrition of tomato and lettuce plants grown in soils of varying acidity.

Extraction by Ethyl Alcohol. Beauchamp and his collaborators, in a series of investigations on the nutrition of sugar cane (Beauchamp 1939 ; 1940a ; Beauchamp and Alvarino, 1940 ; Beauchamp and Lazo, 1938 ; Beauchamp *et al.*, 1934, 1935) and potato (Beauchamp, 1940, 1942) extracted the leaves with alcohol, the extract being referred to as " crude chlorophyll." The extract was analysed for the five principal nutrients, and in samples from plots in field trials receiving different fertilizer treatments a relation was found between the treatment and the composition of the extract. In certain investigations (Beauchamp, 1940a, 1942 ; Beauchamp *et al.*, 1934) the extracted residue (" leaf skeleton ") was analysed as well as the " crude chlorophyll " ; the surprising result was obtained that while the potassium content of the extract was closely related to the potassium status of the plants as shewn by their treatment and growth, that of the " leaf skeleton " shewed no such relation. Consequently the " crude chlorophyll " was considered to provide a better index of the potassium nutrition of the plant than either the extracted residue or the whole leaf material.

The soils on which Beauchamp worked appear to have been deficient only in potassium, so there is no reason to suppose that his results apply equally to other nutrients. Though Das (1936) found that the percentage of alcohol-soluble nitrogen in the sugar cane was increased by nitrogen application more markedly than that of total nitrogen, Eaton's (1941) results with sunflower shew that the same does not apply to sulphur—in fact the alcohol-soluble fraction tended to be higher under conditions of deficiency ; similar results were obtained with black mustard (Eaton, 1942). In relation to potassium, however, Beauchamp's results are sufficiently striking to be well worth testing in other localities and on other crops.

Other Methods of Extraction. In the Purdue University system of tissue tests see (p. 42) and in certain others, the reagents are added directly to the fresh plant material. This amounts to a very brief extraction with the solvent used for the reagent, which in the Purdue tests is concentrated sulphuric acid in the case of nitrate, dilute hydrochloric acid in the case of phosphate, and dilute acetic acid, sometimes with alcohol added, in the case of potassium.

Under the general heading of extraction methods, it is convenient, though perhaps not strictly accurate, to include the use of exuded sap. This seems first to have been proposed by Sabinin and his colleagues (Sabinin, 1928 ; Sabinin *et al.*, 1929) ; since in the sap collected from variously fertilized plots of oats and barley the phosphorus concentration was not closely related to the yield of the plants (although consistently related to the phosphorus fertilizer treatments they had received), the weight of phosphorus contained in the sap gathered over a certain period was considered a more reliable index. Lowry and Tabor (1931) described a method for collecting sap from the cut ends of maize stems for analytical purposes, and Lowry *et al.* (1936) later used this method in investigations on a fertilizer trial. They found that the potassium and phosphorus contents of the sap were higher with fertilizer treatments containing these elements but that the nitrogen content did not reflect the treatments. In West Virginia also (Pierre and Pohlman, 1933 ; Pohlman and Pierre, 1933) analyses of the exuded sap of maize, Sudan grass and sorghum were carried out, and it was found that the phosphorus content was related to the phosphorus status of the soil on which the plants were growing. Evans (1941) found that the composition of the exuded sap of sugar cane reflected deficiencies of potassium and phosphorus. Lundegårdh (1945) made an elaborate study of sap exuded by wheat, and shewed that its composition rapidly altered in accordance with changes in the medium in which the plants were grown.

Oserkowsky (1932) extracted the tracheal sap from branches by displacement. He was not able to find consistent differences in the iron content of the sap from chlorotic and normal branches.

A method, suggested by Spurway (1940) and called " electro-foliar diagnosis," may also find a place here. Leaves were placed between two filter papers moistened with acetic acid, and a potential difference of 45 volts maintained between these filter papers for two minutes. Some of the free ions in the leaves migrated to one or the other filter paper and could there be detected by appropriate colour reactions. This method does not seem to have achieved practical application.

It will be noted that relatively few of the proposed extraction techniques have been subjected to tests in comparison with other possible extraction methods or with analysis of the whole material. It is, of course, true that the arguments and experimental evidence cited above as supporting the use of inorganic or soluble fractions of nitrogen, phosphorus and sulphur rather than their total content or more fully elaborated fractions for diagnostic purpose will also, to some extent, support the use of many of the extraction methods in place of analysis of the whole material, since most of the extraction methods mentioned will remove preferentially the unelaborated fractions of these three elements. These arguments do not, however, apply to determinations of the other nutrient elements ; but it is usually convenient to determine all the nutrient elements under study in the same solution, and the use of the same extract for all determinations can be defended on these practical grounds.

### Chemical and Physico-chemical Methods of Nutrient Determination in Plant Material.

Little need be said here about the chemical methods for determining nutrient elements in whatever material is prepared for analysis. The standard chemical methods—as described, for instance, by Piper (1942a), or those of the Association of Official Agricultural Chemists (Skinner, 1935)—may always be used, though they are often inconveniently lengthy, and unnecessarily accurate considering the large errors between replicate samples of plant material. Several systems of tests specially devised for use with plant material samples have been published ; among them may be mentioned those of Gilbert (1926) ; Emmert (1929, 1929a, 1930, 1932, 1935a, 1935b, 1942a, 1944, 1944a) ; the Purdue University workers (see p. 42) ; Morgan (1935, 1937), also intended for soil extracts ; Hance (1936, 1937, 1941 ; Nishimura and Hance, 1938), also used for soils ; Carolus (1938) ; Wall (1940) ; Parks *et al.* (1943) ; Wolf (1943, 1944, 1944a) ; Lindner and Harley (1942 ; Lindner, 1944) ; Peech and English (1944), whose tests, though primarily intended for soils, were also meant to be applicable to plant extracts, and were in fact so applied by Harrington (1944) and by Boynton and Peech (1945) ; and Plant *et al.* (1945).

The determination of the trace elements in plant material presents special problems because of the small quantities present ; several special colorimetric methods for boron determination have been published, for instance (Berger and Truog, 1939, 1944 ; Maunsell, 1940). Spectrographic methods have been used fairly widely for diagnostic purposes, notably by Lundegårdh (1931, 1932, 1934, 1935, 1938, 1939, 1941, 1943) and Roach (1939a, 1940, 1943 ; Roach and Bolas, 1943 ; Roach *et al.*, 1939) ; others who have reported the use of spectrographic analysis for diagnostic determinations include Jones (1938) ; Sen (1938) ; Gaddum *et al.* (1939) ; Spencer and Lavin (1939) ; Keiller (1939) ; Shear and Ussery (1940) ; Goodall (1943, 1945, 1945a) ; and Vanselow (1945). The polarograph has been found useful for zinc determinations (Hoagland *et al.*, 1937 ; Lyman and Dean, 1942 ; Piper and Walkley, 1943 ; Roach and Bolas, 1944 ; Roach, 1945 ; Riches, 1945).

The neat semiquantitative method of Kidson (Kidson, 1942 ; Cawthron Inst., 1942, 1943 ; N. Z. Dep. sci. industr. Res., 1942) may be mentioned. A leaf is ashed on a porous tile, and the resulting ash skeleton is sprayed with a reagent giving a coloured product with some nutrient element in the leaf ash. Not only the intensity of the colour but also its distribution over the leaf area may be of diagnostic value.

## METHOD OF EXPRESSION AND INTERPRETATION OF RESULTS.

### Methods of Expression of Results of Diagnostic Analysis.

From very early in the history of agricultural chemistry it has been a convention to express chemical analyses in terms of *oxides* of most of the elements—as $P_2O_5$, $K_2O$, CaO, MgO, $Fe_2O_3$ $Al_2O_3$, $SiO_2$ and others. The practice (illogically) was never applied to nitrogen. A good many of the investigators whose work has been under discussion have persisted in this practice—presumably in deference to tradition, for no rational defence of it has been found. Many workers now are, however, expressing their results in terms of elements, and this is almost universal in investigations of the trace elements. The concurrent use of the two forms of expression has sometimes led to ambiguity and misunderstanding. For instance, Burkhart and Page (1941) say that their " results seem to indicate that peanuts . . . . will respond to calcium, potassium and

phosphorus if the concentrations of these soluble mineral nutrients . . . .are much below 4,500, 5,500 and 600 p.p.m. respectively," whereas it is clear from the Tables to which reference is made that these concentrations relate to the oxides ; if the figure of 600 p.p.m. referred to *phosphorus* strictly, none of the figures quoted would approach it, the highest being 750 p.p.m. $P_2O_5$. Hill (1943) also in his text mentions certain internal concentrations of " potassium," whereas corresponding figures in his tables are for $K_2O$. Wallace (1939), in comparing his calcium analyses of apple leaves with those of Garner *et al.* (1930), appears to have misread the latter as CaO, when in fact they were figures for Ca.* Some workers, notably Lundegårdh, have expressed their results in terms of milliequivalents ; however, in the case of elements of variable valency, this involves an assumption as to the form in which they are present in the plant. The practice of expressing results in terms of the weight of the element present has been generally adopted in this paper, and results expressed in other ways have been converted in many cases. The choice between these methods of expression is however, in the main, purely a matter of personal preference and convenience.

If the necessary information is available, the weight of nutrients present in the plant material analysed may be expressed per plant, per leaf, per unit leaf area, or on a basis of fresh weight, dry weight or ash weight. Where sap or an extract has been used for analysis, the results may be reported on a volume basis.

The question of which of these methods of expression is the most appropriate in any particular case should be approached in the same way as the other methodological questions discussed above—that is, the regression should be computed of the yield increment due to fertilizer treatment on mineral content expressed in each of the possible ways, and the method of expression giving the lowest error term when the regression has been fitted should be chosen. This choice must, however, be subject to convenience.

No comparative tests of different methods of expression seem to have been carried out by this rigorous method, although data are available in the literature permitting it to be done—at least under the restriction already mentioned, that fertilizer applications have taken place before the samples were gathered. For instance, the data of McDonald and Rodriguez (1935) on cacao would permit a comparison of the dry weight and ash weight as bases for the expression of results of leaf analysis, and those of Lorenz (1942) on boron content of leaves and roots of beet could be expressed on a basis of fresh weight, dry weight or ash weight.

Results Expressed per Plant or per Leaf. For this, the number of leaves of which the sample consists, or the number of plants represented in it, must be known, together with the weight of the whole sample if only a part of it is analysed ; if the whole is analysed the result will be obtained directly in this form.

Expressing results on a " per plant " basis may be quite impracticable with perennial crops, and may be very troublesome with annual crops, especially when they tiller freely ; it has in fact rarely been proposed as a basis for diagnosis.

In the field, nutrient intake per unit area of ground is a form of expression almost equivalent to content per plant. Münter (1919, 1920) considered this the most suitable index of nitrogen nutrition of wheat, barley and sugar beet, since it showed most clearly the difference between control plots and those receiving a complete fertilizer ; he considered that nitrogen supplies were adequate when the nitrogen uptake of barley straw was more than 9 kg/ha, or when that of sugar beet exceeded 100 kg/ha or that of the tops alone 50 kg/ha, while for wheat the sum of the nitrogen, lime and magnesia taken up should exceed 60 kg/ha in the grain and 30 kg/ha in the straw. However, if his results are recomputed on the basis recommended here it will be found that the correlation of yield increment due to nitrogenous fertilizer with these indices is small ($r = -.2827$, $r = -.4894$ using total uptake of whole plant and yield increment of beet roots or wheat grain respectively) whereas the correlation with percentage of nitrogen in the dry matter is much higher ( $-.7968$, $-.4573$ with percentage in beet roots and tops, $-.7597$ and $-.6375$ with percentage in wheat grain and straw.)

* " the minimum calcium requirement of tobacco, as measured by calcium content of the upper leaves, lies between 1.1 and 1.5 per cent (1.5 to 2.1 per cent CaO) . . . . the minimum content of calcium in the leaf required to prevent deficiency symptoms is in excess of 1 per cent." (Garner *et al.*, 1930) ; " the amounts of the two former " (lime and magnesia) " agreeing well with the amounts stated by Garner *et al.* . . . . as necessary for the healthy growth of the tobacco leaf, viz. above 1.0% CaO and 0.4% MgO." (Wallace, 1939).

Frear and Anthony (1943) computed the nitrogen content per leaf (lamina only) in apple trees receiving different amounts of nitrogenous fertilizer, and concluded that it furnished "a more consistently reliable reflection of nitrogen fertilization" than leaf size. They did not test the possibility of using percentage of nitrogen in the dry matter in the same way, but their data suggest that this would be an even better index than milligrams of nitrogen per leaf. Gossard (1943) found that the variability of nitrogen content per leaf in pecan was much greater than when expressed as a percentage of dry matter, and hence preferred the latter mode of expression. Drosdoff (1944) considered that results of leaf analysis were sometimes better expressed on a unit leaf basis. Martin (1940) used this form of expression for his nitrogen analyses of grapefruit leaves.

Results Expressed Per Unit Leaf Area. This will require measurement of leaf area in such a way as to relate it to the primary basis of expression of the results (whether per leaf, per unit fresh weight, per unit dry weight, etc.) unless the sample is obtained by some such method as the Ganong leaf punch, in which case determining the nutrient content of a given number of punch samples will give the results on an area basis directly. If this is done, however, care must be taken that diurnal changes in area of the leaf (Thoday, 1909) do not vitiate the results.

Lindner (Lindner, 1944 ; Lindner and Harley, 1942, 1944) considers that to express results of leaf analyses on an area basis is often preferable to the more usual dry matter basis. He points out (private communication) that if a nutrient deficiency affects carbohydrate accumulation, differences in composition expressed in these two ways may be far from identical and may even be in opposite senses—the nitrogen content of a chlorotic leaf may be high on a dry matter basis, though low on an area basis. Thorne and Wallace (1944), too, preferred to express their results for leaf composition on an area basis. The fact that, if a leaf punch is used and results expressed on an area basis, weighing the samples can be eliminated is a point of practical value (Hance, 1937 ; Lindner and Harley, 1942 ; Chem. Dept. Exp. Sta., H.S. P.A., 1944) ; some who use leaf punches, however, prefer to express their analytical results on a dry matter basis (Yuen and Hance, 1939 ; Borden, 1942, 1944).

Results Expressed on a Fresh Weight Basis. Where the fresh material or an extract of it is used for analysis, this is the most obvious basis for expressing the results. If, however, material stored in a dry state is used, an estimate of the water content of the fresh material will be needed. Expression of the results of analysis of fresh material extracts on a basis of the volume of the extract may be included under this heading since, provided the experimental procedure is not varied, such results may generally be converted to a fresh weight basis by use of a constant factor. The same applies almost as much to results of analyses of expressed sap quoted per unit volume.

Few comparisons between this and other modes of expression appear to be extant. According to the data of van Ginneken and Bruinsma (1938), the correlation of sugar yield from beets grown in different fields with the nutrient content of their foliage is slightly higher when the latter is expressed on a fresh weight basis than on a dry weight basis. Hilgeman (1941) claimed that, in grapefruit leaves, "percentage of nitrogen on a fresh weight basis . . . presents a more accurate picture of nitrogen levels than the percentage based on the dry weight." Nightingale (1942a) argued that expressing results of analyses of mature tissues on a basis of sap volume avoided the difficulties introduced by differences in the degree of lignification. Iljin (1943) also favoured expressing analytical results on a basis of cell sap.

Most of those who have analysed extracts of fresh material for diagnostic purposes have expressed their results on a fresh weight basis.

Results Expressed on a Dry Weight Basis. This is the most commonly used method of expression, the dry material being the most usual starting point for the analytical process. When the analysis (or the extraction preliminary to analysis) is performed on fresh material, the water content of this fresh material must be known if it is desired to convert the results to a dry matter basis. Thomas and Mack (1939b) considered that a dry matter basis was the only suitable one for expressing the results of diagnostic plant analysis, but did not demonstrate this ; indeed, the method of expressing the primary analytical results would not affect the values of the "NPK-

Unit " on which they largely base their conclusions. (p. 41). Yuen and Hance (1939) considered that, because percentages of nutrients in sugar cane leaf samples were greater on a dry weight than on a fresh weight basis, the former mode of expression was to be preferred.

Results Expressed on an Ash Basis. Many analytical methods involve ashing the material before making determinations for individual nutrient elements. If this is done the results may readily be expressed on an ash basis provided the ash has been weighed. In other cases, a special determination of the ash content of the material would be required. This method of expression is equivalent to determining the ratio of the nutrient element considered to other non-volatile mineral constituents.

Anderssen (1932) found that the differences between the copper content of different parts of normal fruit trees and of others suffering from copper deficiency were more obvious on an ash basis than on a dry weight basis ; indeed, if a deficiency affects assimilation without affecting proportionately the intake of other ash constituents, this is to be expected—but that is not to say that the variability of results expressed on an ash basis may not be greater. Brandenburg (1932, 1939) has shewn that the boron content in the roots of beet suffering from boron deficiency is almost normal on a dry matter basis, but low as a percentage of ash (see Table I). Smith and Nash (1937) regarded variations in the percentage ash content of the dry matter of potato as an argument against expressing analytical results on a dry matter basis. On the other hand, Alway *et al.* (1926) considered that this variation in the percentage ash content, bearing no consistent relation to fertilizer treatment, was a reason for preferring to express results on a dry matter basis. The results of McDonald and Rodriguez (1935) showed that, in a fertilizer trial with cacao in which there were marked responses to potassium-containing fertilizers, the correlation of yield with potassium content of the leaves was higher when the latter was expressed on a dry matter than on an ash basis.

A number of investigators using plant analysis for diagnostic purposes have expressed their results as percentage of ash. Wallace did so in several of his investigations on the nutrition of fruit plants (Wallace, 1928, 1929b ; Wallace and Mann, 1926), as did Hill and Johnston (1940) in their investigation of magnesium deficiency in the apple ; Hardy and his colleagues did the same with cacao and grapefruit (Hardy, 1937 ; Hardy and Rodriguez, 1935 ; Hardy *et al.*, 1935 ; McDonald and Rodriguez, 1935), Follett-Smith (1934, 1939) with sugar cane, de Haan and Schoorel (1940) with tea and Chapman (1941) with rubber.

### Methods of Interpretation of Results of Diagnostic Analysis

Interpretation Based on Percentage Nutrient Content. In interpreting the results of diagnostic analyses, it is of course essential to have standards of reference, and it is equally essential that these analytical standards should be linked with data on the performance of the plants from which they are derived. A practice which has often been adopted is to use analyses of material from a plant or site where the performance was particularly good as a standard, and to regard any deviations from this standard as being due to less satisfactory nutritional conditions, which would account for poorer performance. This is a very inadequate basis for the interpretation of diagnostic analyses, for the standard material might be well within the " luxury consumption " range for several nutrients, and hence a lower percentage of these might involve no diminution in yield and no increased probability of response to fertilizer treatment. This objection is somewhat diminished when a normal range, based on good plants from a considerable number of diverse sites, serves as a basis for comparison ; but even in this case a deduction that the yield of a plant in which the percentage of one nutrient falls below the normal range would be increased by application of a fertilizer containing this nutrient can be little more than speculation, unless the data on which the normal range was based were selected from a wider range of observations covering also plants known to respond to the fertilizer in question. Until the investigator has data on the yield responses of plants at varying levels of nutrition, and on their composition, he is hardly in a position seriously to consider setting up standard values for internal nutrient concentrations.

To base the conclusions from diagnostic analyses on the data for a single element will in general be unsatisfactory. It has already been shewn that the increase in yield to be expected

from increase in the supply of a nutrient is related not only to the internal concentration of that nutrient, but also to that of other nutrients. Consequently a method of interpretation of the results of diagnostic analyses must not only take account of the value for the nutrient primarily considered, but must also allow for variations in the internal concentration of the other nutrients. This seems now to be fairly generally recognized (c.f. Emmert, 1935a ; Hester, 1941 ; Hoffer, in Hambidge, 1941 ; Collins, 1942 ; Drosdoff, 1944), but usually only to the extent that the investigator assures himself that nutrients other than the one under investigation are not " limiting".

The ideal method of interpreting diagnostic analyses so as to allow for the effect of the internal concentration of more than one nutrient on the expected yield increase with the proposed treatment is, as has already been indicated (p. 58), by a multidimensional diagram, or an equivalent algebraic expression. So exhaustive a treatment has never been attempted ; the nearest approach to it has been in the " triple analysis " method of Lundegårdh (1941, 1943), who restricted himself to determining the effect of a single level of treatment with each of the three principal fertilizer elements, and produced graphs connecting the increase in yield as a consequence of these treatments with the content of the nutrient in question in the leaves, within certain specified ranges of content of the other principal nutrients. He considered, however, that a verbal description of the yield increments to be expected with fertilizer treatment at different levels of nutrient content was the most practical way to present his conclusions, and these are summarized in Table VI.

**Table VI**

**Probable effect of fertilizer application on grain yield of oats (from Lundegårdh, 1941)**

(nutrient content of leaves in m.e. per cent. of dry matter)

| | | Very Good | Good | Average | Doubtful | None |
|---|---|---|---|---|---|---|
| Effect of 100-150 kg/ha muriate of potash (40%) in addition to 150-200 kg/ha saltpetre. | | | | | | |
| K content | with P content <4.5 | —— | 10 — 20 | 20 — 40 | 40 — 50 | >50 |
| | with P content 4.5-6.5 | <20 | 20 — 30 | 30 — 50 | 50 — 60 | >60 |
| | with P content >6.5 | <30 | 30 — 40 | 40 — 60 | 60 — 80 | >80 |
| Effect of 150-200 kg/ha superphosphate (20%) in addition to 150-200 kg/ha saltpetre. | | | | | | |
| P content | with N content <100 | —— | —— | 1 — 8 | 8 — 9 | >9 |
| | with N content >100 | 4 | 4 — 6 | 6 — 8 | 8 — 9 | >9 |
| Effect of 150-200 kg/ha saltpetre | | | | | | |
| N content | with P content <4.5 | —— | 20 — 80 | 80 —120 | 120—160 | >160 |
| | with P content 4.5-6.5 | <100 | 100—120 | 120—200 | 200—250 | —— |
| | with P content >6.5 | <120 | 120—200 | 200—250 | —— | —— |

It should be clearly understood that the magnitude of a potential yield response will depend not only on the previous nutritional history of the plant, but also on the amount and type of fertilizer material which it is proposed to apply. The value of such data as those in Table VI is therefore somewhat limited ; for though the probable increases to be expected from fertilizers containing the same element are likely to be related in a simple way depending upon their solubilities and other ascertained characteristics, on the other hand the returns for varying dosages will depend upon the form of the yield dosage relation and this, as we have seen, is dependent upon the level of other factors and therefore cannot be determined except by extensive experiments.

Among the few other workers who, in their standard values for one nutrient, have made allowance for variations in another is Emmert (1942a). He investigated the relation between the yield of tomato plants and the nitrogen content (soluble in acetic acid) of their petioles at various

stages of growth ; the plants were divided into ranges on a basis of their internal nitrogen concentration and the correlation with yield determined within each range (see also Emmert, 1937). The nitrogen value, above which such correlations tended to be negative, was regarded as optimal. The optimum could not, of course, be defined with any accuracy by this method, since its determination depended on the separation of ranges by inspection or by trial and error. Nevertheless, very interesting results were obtained, and among them was the observation that during the fruit-setting period the nitrogen optimum was lower if the soluble phosphorus content was below 200 p.p.m. (of fresh tissue) than if it was above this figure.

Hall (1905) suggested that in the roots of mangolds the need for potassic fertilizers was indicated not by the content of potassium alone, but by the sum of the contents of potassium and sodium. This fits in well with the results of van Schreven (1937) with sugar beet, which shew that not only the incidence of deficiency symptoms, but also the sugar yield in factorial experiments with varying sodium and potassium supply is highly correlated with the sum of the percentages of the two elements in the foliage (for sugar yield, in the water culture experiment $r = 0.940$, $n = 9$ ; in the sand culture experiment $r = 0.899$, $n = 6$) ; but Hale's (1945 and private communication) recent results indicate that, though the appearance of symptoms of potassium deficiency depends upon the internal concentration of both potassium and sodium, the relationship is not as simple as that adumbrated by Hall. It is interesting to note that Atterberg (1888a) obtained somewhat similar results with oats (see p. 14).

Many investigators have neglected the relation of yields or yield responses to fertilizer treatment to the internal concentration of nutrients other than that primarily under study, the assumption being made either tacitly or explicitly that the content of these other nutrients falls within the fairly wide range around the optimum where variations in their internal concentrations would have little effect on diagnostic conclusions. Among such investigators, some have expressed their results in the form of curves. Craig (1940), for instance, presented curves shewing the relation between the concentrations of phosphorus and potassium in sugar cane leaves and the yield response to fertilizers containing these elements ; Crowther (1937) prepared a similar curve for nitrogen in cotton leaves ; and van Itallie (1935) plotted the *percentage* increase in yield of hay with potassic fertilizers against the potash content of hay from untreated plots. The Black Rock Forest workers (Mitchell, 1939 ; Mitchell and Chandler, 1939) published curves connecting the growth of forest trees with the concentration of nitrogen in their leaves. As already mentioned (p. 57), Macy (1936) plotted both his own data and those of a number of other workers in this way.

The majority of workers, however, have merely given verbal descriptions of certain ranges or points in such curves, without attempting to draw the whole curve. Among the earliest of such investigators was Heinrich (1882), whose conclusions are embodied in Table VII.

**Table VII**

**Probable yield of oats in relation to nutrient content of roots at maturity**
**(% of dry matter) (From Heinrich, 1882)**

| | *Low* | *Average* | *High* |
|---|---|---|---|
| N | 0.5 — 0.6 | 0.7 — 0.9 | 0.9 or more |
| $P_2O_5$ | 0.1 — 0.2 | 0.2 — 0.3 | 0.3 or more |
| $K_2O$ | 0.1 — 0.2 | 0.2 — 0.4 | 0.4 or more |
| CaO | 0.2 — 0.3 (?) | 0.3 — 0.4 | 0.4 or more |

Remy (1903b) characterized the phosphorus status of hop plants, as indicated by the composition of mature leaves sampled at breast height during the burr stage ("*Anflug*"), as follows :

**Table VIII**

**Phosphorus status of hops (From Remy, 1903b)**

| | $P_2O_5$ in leaves. |
|---|---|
| Phosphorus in relative excess | >0.60 |
| Phosphorus in adequate supply | 0.55 — 0.60 |
| Phosphorus relatively deficient | 0.50 — 0.55 |
| Phosphorus seriously deficient | <0.50 |

Wagner (1909) and his followers related the effect of potassium-containing fertilizers to the potash content of mixed hay as shewn in Table IX ; the conclusions of van Itallie (1935), to whom reference has already been made, are also included :—

**Table IX.**

**Relation of the effect of potassium-containing fertilizers on the yield of grassland to the potash content of mixed hay.**

| Effect of fertilizer according to Wagner (1909) | $K_2O$% in hay (With 14% moisture) | Need for fertilizer (according to Wiegner (1933)) | $K_2O$% in hay (With 14% moisture) | Effect of fertilizer according to van Itallie (1935) | $K_2O$% in hay (dry matter) |
|---|---|---|---|---|---|
| Soil supply adequate | 2.0 or more | Unnecessary | >2.0 | Yield increase unlikely | 2.35 |
| Possibility of yield increase. | 1.8 | Possibly advantageous | 1.6—2.0 | Possibility of yield increase | 2.00—2.35 |
| Probability of yield increase | 1.6 | Probably advantageous | 1.2—1.6 | Probability of yield increase. | 2.00 |
| Very great probability of yield increase. | 1.4 | | | | |
| Certainty of yield increase. | 1.2 or less | Certainly necessary | <1.2 | | |

Borden (1936a) characterized four levels for the potassium and phosphorus content of the crusher juice of sugar cane as follows :—

**Table X**

**Percentages of nutrients in crusher juice of sugar cane at different levels of deficiency. (From Borden, 1936a)**

| | % $P_2O_5$ | % $K_2O$ |
|---|---|---|
| Low | 0.025 | 0.15 |
| Doubtful | 0.030 | 0.20 |
| Medium | 0.035 | 0.25 |
| High | 0.045 | 0.35 |

These results were obtained with the variety H.109, and Borden adds that they " may not be reliable for other cane varieties or for H.109 grown under different conditions."

Teakle and Turton (1943) gave a similar table for the copper content of leaves of subterranean clover—not in relation to the response of the clover itself to copper treatment, but to the status of other crop plants and stock in the area :—

**Table XI**

**Copper content of leaves of subterranean clover (p.p.m. in dry matter) as indicating the copper status of the area (From Teakle and Turton, 1943).**

| | |
|---|---|
| Deficient | <3 |
| Subnormal | 3-4.5 |
| Low normal | 4.5-7.5 |
| Normal | 7.5-15 |
| Rich | >15 |

All these verbal descriptions of the nutrient status of plants falling within successive ranges of nutrient content may be regarded as the equivalent of histograms representing roughly the multidimensional diagrams which we have indicated as the ideal way of expressing these relationships, with most of the dimensions omitted.

Most investigators have not attempted to specify a series of successive ranges of different nutrient status, as in Tables VI-XI, but have merely suggested certain values or ranges of nutrient content as characterizing particular parts of the hypothetical curves. Many, for instance, have specified optimal levels or ranges, or limiting values above which the nutrient supply may be regarded as adequate and no response to fertilizers may be expected. Macy's (1936) " critical percentages " fall into the latter category, Ulrich (1943) suggested that critical percentages could be found by periodical determinations on plants at two nutritional levels ; the percentages in plants at the lower supply level at the time when an effect of deficiency on growth first became apparent was taken as critical. Some early workers (von Dikow, 1891 ; Helmkampf, 1892) regarded the nutrient content as subject to a maximum (see p. 13) at which level, apparently, fertilizer effects would be negligible. Some of the early workers, too, basing themselves upon Liebig's " Law of the Minimum," considered that when the supply of a nutrient was " in minimum " its content in the plant also tended towards a minimum percentage, and the more the nutrient content exceeded this percentage, the less would responses to fertilizers containing the nutrient be ; in this connection, it is interesting to note that Chapman (1941) in his observations on the relation between growth of rubber trees and the nutrient content of their leaves, was able to estimate what appears to be a true minimum—namely, he found that extrapolation of the curve for phosphorus gave zero growth at 3% $P_2O_5$ in the ash.

A summary of many of these " optimal," " minimal," " normal " and " limiting " values quoted in the literature is given in Table XII.

## TABLE XII.

**Standard values of nutrient content proposed in the literature.**

*N.B.—Letters in brackets refer to Notes at end of table.*

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated) | Reference |
|---|---|---|---|---|---|
| APPLE (*Pyrus malus*, etc). | | | | | |
| | N | ———— | Leaves | Growth limited when N% < 1.70 | Boynton, 1942 |
| | N | ———— | Leaves | "Fair chances for both good production and good colour" when N% = 1.80-2.00 | Boynton, 1942 |
| | N | July | Leaves | Optimum yield when N% > 1.85 | Boynton & Burrell, 1944 |
| | N | Midsummer | Shoot leaves | Optimum N% = 1.85-2.00 | Boynton & Compton, 1945 |
| | K | ———— | Leaves | Optimum growth when K% > 1.70 | Batjer & Magness, 1939 |
| | K | ———— | Leaves | Response to K fertilizer treatment when K% < 0.75 | Boynton & Peech, 1945 |
| | Mg | ———— | Leaves | Response to Mg fertilizer treatment when Mg% < 0.20 | Boynton & Peech, 1945 |
| | B | Harvest | Fruit | Deterioration in keeping quality when B% > 0.0020 | Chittenden & Thomson, 1938 |
| | Cu | ———— | Leaves | Cu supply inadequate when Cu% < 0.0004 | Teakle, 1942 |
| ASTRAGALUS *racemosus* | | | | | |
| | Se | ———— | Tops | Growth reduced when Se% > 0.2 | Trelease & Trelease, 1938 |
| BARLEY (*Hordeum vulgare*) | | | | | |
| | N | Harvest | Straw | Minimum N% (*see* p. 57) = 0.4 | Macy, 1936 |
| | N | Harvest | Straw | "Critical percentage" of N (see pp. 57, 58) = 0.8 | Macy, 1936 |
| | N | Harvest | Grain | "Critical percentage" of N (see pp. 57, 58) = 2.2 | Macy, 1936 |
| | N | Harvest | Roots | Minimum N% (*see* p. 57) = 0.63 | von Dikow, 1891 |
| | P | Harvest | Straw | Consistent response to P fertilizer treatment when P% < 0.18 | Wagner, 1915 |
| | P | Harvest | Straw | Consistently *no* response to P fertilizer treatment when P% > 0.30 | Wagner, 1915 |
| | P | Harvest | Roots | Minimum P% (*see* p. 13) = 0.057 | von Dikow, 1891 |
| | K | Harvest | Straw | K% necessary for maximum yield = 0.42 | Hellriegel, 1867 |
| | K | Harvest | Straw | K supply inadequate when K% < 0.83 | Godlewski, 1901 |
| | K | Harvest | Grain | K% necessary for maximum yield = 0.32 | Hellriegel, 1867 |
| BASSWOOD (*Tilia* spp.) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 3.12-3.15 | Mitchell & Chandler, 1939 |
| | N | Near end of season | Leaves | Cannot compete effectively when N% < 2.32 | Mitchell & Chandler, 1939 |
| BEECH (*Fagus grandifolia*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.77-2.85 | Mitchell & Chandler, 1939 |
| BEET (*Beta vulgaris*) [*see also* Mangold, Sugar Beet] | | | | | |
| | N | ———— | Leaf laminae | Minimum $NO_3$- N% (for satisfactory growth?) = 0.05 (I,O) | R. I. agric. Exp. Sta., 1935 |
| | N | ———— | Leaf laminae | Minimum $NO_3$-N% (for satisfactory growth?) = 0.15 (I,P) | R. I. agric. Exp. Sta., 1935 |
| | N | ———— | Petioles & midribs | Minimum $NO_3$-N% (for satisfactory growth?) = 0.005 (I,O) | R. I. agric. Exp. Sta., 1935 |
| | N | ———— | Petioles & midribs | Minimum $NO_3$-N% (for satisfactory growth?) = 0.03 (I,P) | R. I. agric. Exp. Sta., 1935 |

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | | Reference |
|---|---|---|---|---|---|---|
| BLACK GUM (*Nyssa sylvatica*) | | | | | | |
| | N | Near end of season | Leaves | Optimum | N% = 2.75-2.85 | Mitchell & Chandler, 1939 |
| CABBAGE (*Brassica oleracea*) | | | | | | |
| | N | ———— | Midribs (?) | Optimum | $NO_3$-N% = 0.03 (I) | Gilbert & Smith, 1929 |
| CACAO (*Theobroma cacao*) | | | | | | |
| | N | ———— | Young leaves | N% on standard good plots | = 2.35 | McDonald, 1934 |
| | P | ———— | Young leaves | P% on standard good plots | = 0.219 | McDonald, 1934 |
| | K | ———— | Young leaves | K% on standard good plots | = 2.19 | McDonald, 1934 |
| CARROT (*Daucus carota*) | | | | | | |
| | P | Active growth period | Petioles (C?) | Reduction in yield when | P% < 0.0125 (G) | Hill, 1943 |
| CELERY (*Apium graveolens*) | | | | | | |
| | N | First third of growth period | Leaf laminae | Optimum | $NO_3$-N% = 0.02 (I) | R. I. agric. Exp. Sta., 1935 |
| | N | Last two-thirds of growth period | Leaf laminae | Optimum | $NO_3$-N% = 0.03-0.04 | R. I. agric Exp. Sta., 1935 |
| | N | First third of growth period | Petioles & midribs | Optimum | $NO_3$-N% = 0.04 (I) | R. I. agric. Exp. Sta., 1935 |
| | N | Last two-thirds of growth period | Petioles & midribs | Optimum | $NO_3$-N% = 0.06 (I) | R. I. agric. Exp. Sta., 1935 |
| | N | ———— | Stems (?) | Optimum | $No_3$-N% = 0.03 (L) | Gilbert & Smith, 1929 |
| CHESTNUT OAK (*Quercus montana*) | | | | | | |
| | N | Near end of season | Leaves | Optimum | N% = 2.72-2.80 | Mitchell & Chandler, 1939 |
| CITRUS (*Citrus* spp.) [*see also* Grapefruit] | | | | | | |
| | K | July-Sept. | Spring-cycle leaves from fruit-bearing branches | K supply ample when | K% > 1.0 | Chapman & Brown, 1943, 1943a ; Chapman *et al.*, 1944 |
| CLOVER (*Trifolium* sp.) [*see also* Subterranean Clover]. | | | | | | |
| | P | ———— | Petioles (C) | P supply inadequate when | $PO_4$-P% < 0.06 | Ulrich, 1944a |
| | K | ———— | Petioles (C) | K supply inadequate when | K% < 0.8 | Ulrich, 1944a |
| CORSICAN PINE (*Pinus laricio* var. *Corsicana*) | | | | | | |
| | N | Seedling stage | Plant | Optimum | N% = 3.0 | Gast, 1937, from data of Aldrich-Blake, ? 1930 |
| FIELD BEAN (*Vicia faba*) | | | | | | |
| | Mn | Harvest | Leaves | Response to Mn fertilizer treatment when | Mn% < 0.01 | Marsh & Powers, 1945 |
| FLAX (*Linum usitatissimum*) | | | | | | |
| | K | Harvest | Straw | K supply inadequate when | K% < 0.58 | Nicholas 1945 |
| GRAPE (*Vitis vinifera* etc) | | | | | | |
| | N | Autumn | Leaves (of bearing vines) | No response to N fertilizer treatment when | N% > 1.56 | Wagner, 1907 |
| | N | Autumn | Yellowing leaves | N supply adequate when | N% > 1.55 | Wagner, 1911, 1924 |

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | | Reference |
|---|---|---|---|---|---|---|
| GRAPE (*Vitis vinifera* etc.)—continued | | | | | | |
| | P | Autumn | Leaves (of bearing vines) | No response to P fertilizer treatment when | P% > 0.19 | Wagner, 1907 |
| | P | Autumn | Yellowing leaves | P supply adequate when | P% > 0.20 | Wagner, 1911, 1924 |
| | K | Autumn | Leaves (of bearing vines) | No response to K fertilizer treatment when | K% > 1.03 | Wagner, 1907 |
| | K | Autumn | Yellowing leaves | K supply adequate when | K% > 1.04 | Wagner, 1911, 1924 |
| | Cu | ——— | Leaves | Cu supply inadequate when | Cu% < 0.0004 | Teakle, 1942 |
| | Cu | Mid-Dec. (Q) | Leaves | Vigorous growth when | Cu% = 0.00075-0.00100 | Teakle *et al.*, 1943 |
| GRAPEFRUIT (*Citrus paradisi*) [*see also* Citrus] | | | | | | |
| | N | ——— | Leaves | Standard | N% = 2.38 | Hardy & Rodriguez, 1935; Hardy *et al.*, 1935 |
| | N | Apr. | Leaves | Optimum | N% = 2.1-2.2 | Finch, 1944; Jones 1944 |
| | N | Sept.-Nov. | Leaves | Optimum | N% = 1.2 | Finch, 1944; Jones 1944 |
| | P | ——— | Leaves | Standard | P% = 0.16 | Hardy & Rodriguez, 1935; Hardy *et al.*, 1935 |
| | K | ——— | Leaves | Standard | K% = 1.05 | Hardy & Rodriguez, 1935; Hardy *et al.*, 1935 |
| | Ca | ——— | Leaves | Standard | Ca% = 6.13 | Hardy & Rodriguez, 1935; Hardy *et al.*, 1935 |
| HAY (mixed) [*see also* Table IX]. | | | | | | |
| | P | ——— | ——— | P supply adequate when | P% > 0.31 | Hoffman, 1913; Wagner, 1909 |
| | P | First cut | ——— | P supply inadequate when | P% < 0.24 | Liechti & Ritter, 1917 |
| | P | Second cut | ——— | P supply inadequate when | P% < 0.28 | Liechti & Ritter, 1917 |
| | P | First cut | ——— | No P fertilizer treatment needed when | P% > 0.23 | Wiegner, 1933 |
| | P | First cut | ——— | No response to P fertilizer treatment when | P% > 0.30 | van Itallie, 1935 |
| | P | First cut | ——— | Response to P fertilizer treatment when | P% < 0.22 | van Itallie, 1935 |
| | K | ——— | ——— | Response to K fertilizer treatment when | K% < 1.66 | Hoffmann, 1913 |
| | K | ——— | ——— | Response to K fertilizer treatment when | K% < 1.79-1.91 | Liechti & Ritter, 1917 |
| | Ca | ——— | ——— | Response to Ca fertilizer treatment when | Ca% < 0.70 | Hoffmann, 1913 |
| HOP (*Humulus lupulus*) [*see* Table VIII] | | | | | | |
| LETTUCE (*Lactuca sativa*) | | | | | | |
| | N | Plants 3"-4" high | Older midribs (C) | Optimum | N% = 0.15-0.20 (G) | Emmert, 1935a |
| | N | Plants 6"-8" high | Older midribs (C) | Optimum | N% = 0.08-0.10 (G) | Emmert, 1935a |
| | P | Plants 3"-4" high | Older midribs (C) | Optimum | P% = 0.015-0.020 (G) | Emmert, 1935a |
| | P | Plants 6"-8" high | Older midribs (C) | Optimum | P% = 0.0100-0.0125 (G) | Emmert, 1935a |
| LIMA BEAN (*Phaseolus lunatus*) | | | | | | |
| | N | Harvest | Stems (D) | Good set when | N% > 0.225 | Wolf, 1942 |
| | Ca | Harvest | Stems (D) | Good set when | Ca% > 0.9 | Wolf, 1942 |
| | Ca | Harvest | Stems (D) | Poor set when | Ca% < 0.6 | Wolf, 1942 |

| Plant | Element | Time or stage of development | Part of plant. | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference. |
|---|---|---|---|---|---|
| LUCERNE (*Medicago sativa*) | | | | | |
| | K | ——— | Tops | Yield decreased when K%<1.0 | Hunter *et al.*, 1943; Bear & Prince, 1945 |
| | Ca | ——— | Tops | Yield decreased when Ca%>2.0 | Hunter *et al.*, 1943 |
| | S | ——— | Tops | "Critical percentage" of S=0.2 (see pp. 57, 58) | Macy, 1936, quoting Alway, 1927 |
| | B | Late summer | ——— | Normal when B%>0.0020 | Dregne & Powers, 1942 |
| MAIZE (*Zea mays*) | | | | | |
| | N | Late summer | Lower stem (A) | N supply adequate when $NO_3$-N%=0.0200 (I) | Pettinger, 1931 |
| | N | ——— | ——— | Response to N fertilizer treatment probable when N%<0.70 | Macy, 1936, quoting Fraps, 1912 |
| | P | Late summer | Lower stem (A) | Good yields when P%>0.0087 (I) | Pettinger, 1931 |
| | P | Late summer | Lower stem (A) | P supply inadequate when P%<0.0044 (I) | Pettinger, 1931 |
| | K | Late summer | Lower stem (A) | K supply inadequate when K%<0.083 (I) | Pettinger, 1931 |
| | K | Late summer | Lower stem (A) | K supply ample when K%>0.166 (I) | Pettinger, 1931 |
| MANGOLD (*Beta vulgaris*) [*see also* Beet] | | | | | |
| | P | Harvest | Root | Consistent response to P fertilizer treatment when P%<0.15 | Wagner, 1915 |
| | B | Harvest | Leaves | Response to B fertilizer treatment when B%<0.0030 | Brandenburg, 1939 |
| OATS (*Avena sativa*) [*see also* Tables VI & VII] | | | | | |
| | N | Harvest | Straw | Minimum N% (see p. 14) =0.25 | Atterberg, 1888, 1889 |
| | N | Harvest | Straw | No increase in yield with increase in N% above 1.0-1.1 | Pfeiffer *et al.*, 1912 |
| | N | Harvest | Grain | Minimum N% (see p. 14) =1.20 | Atterberg, 1901 |
| | N | Harvest | Grain | No increase in yield with increase in N% above 2.2-2.3 | Pfeiffer *et al.*, 1912 |
| | N | Milk-ripe | Tops | N supply adequate when N%=1.10 | Liebscher *et al.*, 1898 |
| | N | Flowering | Tops | Minimum N% (see p. 14) =0.68 | Atterberg, 1901 |
| | N | Milk-ripe | Tops | Minimum N% (see p. 17) =0.759 | Pfeiffer *et al.*, 1915 |
| | N | Milk-ripe | Tops | "Critical percentage" of N =1.0 (see pp. 57, 58) | Macy, 1936; quoting Pfeiffer *et al.*, 1919 |
| | N | Harvest | Roots | Minimum N% (see p. 13) =0.5-0.6 | Heinrich, 1882 |
| | N | Harvest | Plant (?) | Good average development when N%=1.0 | Wolff, 1876, 1877 |
| | N | Harvest | Plant (?) | Minimum N% (see p. 12) =0.6-0.7 | Wolff, 1876, 1877 |
| | N | Harvest | Plant (?) | Minimum N% (see p. 14) =0.80 | Atterberg, 1901 |
| | P | Flowering | Leaves | Normal range of P%=0.23-0.31 | Lundegårdh, 1938 |
| | P | Flowering | Leaves | Growth retarded when P%<0.23 | Lundegårdh, 1938 |
| | P | Flowering | Leaves | Normal range of P%=0.155-0.310 | Lundegårdh, 1939 |
| | P | Harvest | Straw | Consistent response to P fertilizer treatment when P%<0.085 | Wagner, 1915 |
| | P | Harvest | Straw | Consistently no response to P fertilizer treatment when P%>0.184 | Wagner, 1915 |
| | P | Harvest | Grain | P supply inadequate when P%=0.26-0.31 (E) | Atterberg, 1888a |
| | P | Harvest | Grain | P supply adequate when P%=0.39-0.43 (E) | Atterberg, 1888a |
| | P | Harvest | Grain | Minimum P% (see p. 14) =0.16 | Atterberg, 1901 |
| | P | Milk-ripe | Tops | P supply adequate when P%>0.15 | Liebscher *et al.*, 1898 |
| | P | Flowering | Tops | Minimum P% (see p. 14) =0.06 | Atterberg, 1901 |
| | P | Milk-ripe | Tops | Minimum P% (see p. 17) =0.19 | Pfeiffer *et al.*, 1915 |
| | P | Harvest | Roots | Minimum P% (see p. 13) =0.03-0.04 | Heinrich, 1882 |
| | P | Harvest | Plant (?) | Good average development when P%=0.22 | Wolff, 1876, 1877 |
| | P | Harvest | Plant (?) | Minimum P% (see p. 12) =0.15 | Wolff, 1876, 1877 |

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference |
|---|---|---|---|---|---|
| OATS (*Avena sativa*) [*see also* Tables VI & VII]—continued | | | | | |
| | P | Harvest | Plant | Yield decreased when P% < 0.13 | Petersen, 1876 |
| | P | Harvest | Plant | Minimum P% (see p. 14) = 0.09 | Atterberg, 1901 |
| | K | Flowering | Leaves | Normal range of K% = 0.78-1.56 | Lundegårdh, 1938 |
| | K | Flowering | Leaves | Normal range of K% = 0.39-1.56 | Lundegårdh, 1939 |
| | K | Harvest | Straw | K supply inadequate when K% < 0.83 (F) | Atterberg, 1888a |
| | K | Harvest | Straw | Minimum K% (see p. 14) = 0.23 | Atterberg, 1901 |
| | K | Harvest | Straw | Response to K fertilizer treatment when K% < 0.83 | Hoffmann, 1917 |
| | K | Milk-ripe | Tops | K supply adequate when K% = 1.15-1.27 (N) | Liebscher *et al.*, 1898 |
| | K | Flowering | Tops | Minimum K% (see p. 14) = 0.31 | Atterberg, 1901 |
| | K | Harvest | Roots | Minimum K% (see p. 13) = 0.07-0.08 | Heinrich, 1882 |
| | K | Harvest | Plant (?) | Good average development when K% = 0.66 | Wolff, 1876, 1877 |
| | K | Harvest | Plant (?) | Minimum K% (see p. 12) = 0.42 | Wolff, 1876, 1877 |
| | K | Harvest | Plant (?) | Minimum K% (see p. 14) = 0.31 | Atterberg, 1901 |
| | Ca | Flowering | Leaves | Optimum Ca% = 0.176 | Lundegårdh, 1934, 1935 |
| | Ca | Flowering | Leaves | Retarding effect when Ca% > 0.9 | Lundegårdh, 1935 |
| | Ca | Flowering | Leaves | Normal range of Ca% = 0.72-1.0 | Lundegårdh, 1938 |
| | Ca | Flowering | Leaves | Normal range of Ca% = 0.176-1.0 | Lundegårdh, 1939 |
| | Ca | Harvest | Straw | Minimum Ca% (see p. 14) = 0.10 | Atterberg, 1901 |
| | Ca | Harvest | Tops | Minimum Ca% necessary for good development = 0.21 | Wolff, 1868 |
| | Ca | Flowering | Tops | Minimum Ca% (see p. 14) = 0.07 | Atterberg, 1901 |
| | Ca | Harvest | Plant (?) | Good average development when Ca% = 0.18 | Wolff, 1876, 1877 |
| | Ca | Harvest | Plant (?) | Minimum Ca% (see p. 12) = 0.11 | Wolff, 1876, 1877 |
| | Ca | Harvest | Plant (?) | Minimum Ca% (see p. 14) = 0.06 | Atterberg, 1901 |
| | Mg | Flowering | Leaves | Normal Mg% = 0.24 | Lundegårdh, 1938 |
| | Mg | Harvest | Straw | Minimum Mg% (see p. 14) = 0.05 | Atterberg, 1901 |
| | Mg | Flowering | Tops | Minimum Mg% (see p. 14) = 0.05 | Atterberg, 1901 |
| | Mg | Harvest | Plant (?) | Good average development when Mg% = 0.12 | Wolff, 1876, 1877 |
| | Mg | Harvest | Plant (?) | Minimum Mg% (see p. 12) = 0.06 | Wolff, 1876, 1877 |
| | Mg | Harvest | Plant (?) | Minimum Mg% (see p. 14) = 0.06 | Atterberg, 1901 |
| | S | Harvest | Straw | Minimum S% (see p. 14) = 0.06 | Atterberg, 1901 |
| | S | Harvest | Plant (?) | Good average development when S% = 0.08 | Wolff, 1876, 1877 |
| | S | Harvest | Plant (?) | Minimum S% (see p. 12) = 0.04 | Wolff, 1876, 1877 |
| | S | Harvest | Plant (?) | Minimum S% (see p. 14) = 0.10 | Atterberg, 1901 |
| | Cu | 6-9 weeks | Leaves | Cu supply highly inadequate when Cu% < 0.0003 | Teakle, 1942 |
| | Cu | 6-9 weeks | Leaves | Cu supply adequate when Cu% = 0.0007-0.0012 | Teakle, 1942 |
| | Zn | 6-8 weeks | Plant (?) | Zn supply normal when Zn% = 0.0020 | Teakle & Turton, 1943 |
| PEA (*Pisum sativum*) | | | | | |
| | K | Flowering | Main stems (C?) | Optimum K% = 0.415-0.581(G) | Hill, 1943 |
| PEACH (*Prunus persica*) | | | | | |
| | P | Midsummer | Leaves | Growth affected when P% < 0.11 | Lilleland & Brown, 1942, from data of Cullinan *et al.*, 1939 |
| | K | June-July | Leaves | No response to K fertilizer treatment when K% > 1.5 | McCollam, 1943 |
| PEANUT (*Arachis hypogaea*) | | | | | |
| | P | Early part of growing season | Lower leaf blades (B) | Response to P fertilizer treatment when P% < 0.0262 (G) | Burkhart & Page, 1941 |
| | K | Early part of growing season | Lower leaf blades (B) | Response to K fertilizer treatment when K% < 0.46(G) | Burkhart & Page, 1941 |

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference |
|---|---|---|---|---|---|
| PEANUT (*Arachis hypogaea*)—continued | | | | | |
| | Ca | Early part of growing season | Lower leaf blades (B) | Response to Ca fertilizer treatment when Ca% < 0.32(G) | Burkhart & Page, 1941 |
| PEAR (*Pyrus communis*) | | | | | |
| | Cu | ———— | Leaves | Cu supply inadequate when Cu% < 0.0004 | Teakle, 1942 |
| PECAN (*Carya pecan*) | | | | | |
| | P | Early June | Mature leaflets | Response to P fertilizer treatment when P% < 0.150 | Alben & Hammar, 1940 |
| PIGNUT HICKORY (*Hicoria glabra*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.37-2.42 | Mitchell & Chandler, 1939 |
| PINEAPPLE (*Ananas sativus*) | | | | | |
| | N | 14 months before flower-bud appearance | Leaf bases | N supply adequate when $NO_3$-N% = 0.0283 (GHR) | Nightingale, 1942, 1942a |
| | N | 4-10 months before flower-bud appearance | Leaf bases | N supply adequate when $NO_3$-N% = 0.104 (GHR) | Nightingale, 1942, 1942a |
| | P | Early vegetative stages | Leaf bases | P supply adequate when P% = 0.020 (G) | Nightingale, 1942a |
| | P | Blossom-bud differentiation | Leaf bases | P supply adequate when P% = 0.028 (G) | Nightingale, 1942a |
| | K | ———— | Leaf bases | K supply adequate when K% = 0.38 (G) | Nightingale, 1942a |
| PLUM (*Prunus domestica*) | | | | | |
| | K | ———— | Leaves | Normal minimum range of K% = 1.5-2.0 | Boynton, 1942 |
| POTATO (*Solanum tuberosum*) | | | | | |
| | N | 1 month after emergence | 2nd or 3rd petioles from apex | Yield depressed when $No_3$-N% < 0.08 (G) | Lorenz, 1944 |
| | N | ———— | Lower stems (C) | Optimum N% > 0.1 (G) | Emmert, 1936 |
| | N | ———— | Lower stems (A) | N supply inadequate when N% < 0.07-0.08 (F) | Carolus, 1937 |
| | P | Tuberization | Lower stems (C) | Optimum $PO_4$-P% > 0.02 (G) | Emmert, 1936 |
| | P | Beginning of season | Lower stems (A) | P supply inadequate when P% < 0.015 (I) | Carolus, 1937 |
| | P | End of season | Lower stems (A) | P supply inadequate when P% < 0.006 (I) | Carolus, 1937 |
| | P | Harvest | Tubers | Consistent response to P fertilizer treatment when P% < 0.17 | Wagner, 1915 |
| | P | Harvest | Tubers | P supply inadequate when P% < 0.178 | Chaminade, 1942 |
| | K | Beginning of season | Lower stems (A) | K supply inadequate when K% < 0.18 (I) | Carolus, 1937 |
| | K | End of season | Lower stems (A) | K supply inadequate when K% < 0.37 (I) | Carolus, 1937 |
| | K | ———— | Lower stems (A) | Response to K fertilizer treatment when K% < 0.29 (G) | Carolus, 1938 |
| | K | Harvest | Tubers | Consistent response to K fertilizer treatment when K% < 1.49 | Wagner, 1915 |
| | K | Harvest | Tubers | Consistently no response to K fertilizer treatment when K% > 2.49 | Wagner, 1915 |
| | K | Harvest | Tubers | K supply inadequate when K% < 2.38 | Chaminade, 1942 |

| Plant | Element | Time or stage of development | Part of plant. | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference. |
|---|---|---|---|---|---|
| POTATO (*Solanum tuberosum*)—continued | | | | | |
| | Ca | Beginning of season | Lower stems (A) | Ca supply inadequate when Ca% < 0.043 (I) | Carolus, 1937 |
| | Ca | End of season | Lower stems (A) | Ca supply inadequate when Ca% < 0.10 (I) | Carolus, 1937 |
| | Mg | Beginning of season | Lower stems (A) | Mg supply inadequate when Mg% < 0.0166 (I) | Carolus, 1937 |
| | Mg | End of season | Lower stems (A) | Mg supply inadequate when Mg% < 0.048 (I) | Carolus, 1937 |
| | Mg | Harvest | Tubers | Mg supply adequate when Mg% > 0.101 | Chaminade, 1942 |
| RED MAPLE (*Acer rubrum*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.55-2.68 | Mitchell & Chandler, 1939 |
| RED OAK (*Quercus borealis*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.46-2.57 | Mitchell & Chandler, 1939 |
| RYE (*Secale cereale*) | | | | | |
| | P | Harvest | Straw | Consistent response to P fertilizer treatment when P% < 0.06 | Wagner, 1915 |
| | P | Harvest | Straw | Consistently *no* response to P fertilizer treatment when P% > 0.12 | Wagner, 1915 |
| | K | Harvest | Straw | Consistent response to K fertilizer treatment when K% < 0.66 | Wagner, 1915 |
| | K | Harvest | Straw | Consistently *no* response to K fertilizer treatment when K% > 0.95 | Wagner, 1915 |
| SCOTS PINE (*Pinus sylvestris*) | | | | | |
| | N | Seedling stage | Plant | Optimum N% = 3.0 | Gast, 1937 |
| SOY BEAN (*Glycine soja*) | | | | | |
| | B | Harvest | Plant (?) | Reduction in yield when B% < 0.0030 | Muhr, 1941 |
| SUBTERRANEAN CLOVER (*Trifolium subterraneum*) [*see also* Table XI; and Clover] | | | | | |
| | Cu | Flowering | Leaves | Cu supply inadequate when Cu% < 0.0003 | Teakle, 1942 |
| | Cu | Flowering | Leaves | Cu supply adequate when Cu% = 0.0007-0.0012 | Teakle, 1942 |
| | Zn | Flowering | Leaves | Zn supply inadequate when Zn% < 0.0015 | Teakle & Turton, 1943 |
| SUGAR BEET (*Beta vulgaris*) [*see also* Beet] | | | | | |
| | N | ———— | Petioles of younger mature leaves | N supply inadequate when $NO_3$-N% < 0.1 | Ulrich, 1944 |
| | P | ———— | Petioles of younger mature leaves | P supply inadequate when $PO_4$-P% < 0.1 | Ulrich, 1944 |
| | P | Harvest | Tops | P supply inadequate when P% < 0.17 | Münter, 1920 |
| | P | Harvest | Roots | Consistent response to P fertilizer treatment when P% < 0.13 | Wagner, 1915 |
| | K | ———— | Petioles of younger mature leaves | K supply inadequate when K% < 2.0 | Ulrich, 1944 |
| | K | Early harvest | Tops | K supply inadequate when K% < 0.274 (F, G) | van Ginneken & Bruinsma, 1938 |
| | K | Harvest | Roots | Consistent response to K fertilizer treatment when K% < 0.66 | Wagner, 1915 |
| | B | Harvest | Leaves | Response to B fertilizer treatment when B% < 0.0030 | Brandenburg, 1939 |
| | Mn | Harvest | Leaves | Response to Mn fertilizer treatment when Mn% < 0.01 | Marsh & Powers, 1945 |

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference |
|---|---|---|---|---|---|
| SUGAR CANE (*Saccharum officinarum*) [*see also* Table X] | | | | | |
| | N | 6—8 months | Punch samples from centre of laminae of 2nd-4th leaves from apex | Optimum N%=2.0 | Yuen & Hance, 1939 : Doi, 1944 |
| | N | 12-14 months | Punch samples from centre of laminae of 2nd-4th leaves from apex | Optimum N%=1.5 | Yuen & Hance, 1939 |
| | N | 15-17 months | Punch samples from centre of laminae of 2nd-4th leaves from apex | Optimum N%=1.25 | Yuen & Hance, 1939 |
| | N | 24 months | Punch samples from centre of laminae of 2nd-4th leaves from apex | Optimum N%=1.1 | Yuen & Hance, 1939 |
| | N | ——— | Punch samples from centre of laminae of 2nd-4th leaves from apex | Growth diminished when N%<1.3(S) | Yuen & Hance, 1939 |
| | N | ——— | Punch samples from centre of laminae of 2nd-4th leaves from apex | Growth diminished when N%<1.0(T) | Yuen & Hance, 1939 |
| | N | Feb.-April (Q) | Blade of 3rd leaf from apex | Optimum N%=1.38 | Craig, 1941 |
| | N | ——— | Leaf blades from elongating cane | N% adequate for maximum yield =1.0 (H) | Clements & Kubota, 1943 |
| | N | Jan.-Apr. (Q) (5-6 months) | Blade of 3rd leaf from apex | Optimum N%=1.35-1.45 (M) | Craig & Halais, 1944 |
| | N | First 5-6 months | Blades of 3rd-6th leaves from apex | Optimum N%=1.80-2.00 | Clements *et al.*, 1945 |
| | N | Middle of growth period | Blades of 3rd-6th leaves from apex | Optimum N%=1.60 | Clements *et al.*, 1945 |
| | N | Harvest | Blades of 3rd-6th leaves from apex | Optimum N%=1.25-1.35 | Clements *et al.*, 1945 |
| | P | ——— | Blade of 3rd leaf from apex | Response to P fertilizer treatment when P%<0.13 | Craig, 1940 |
| | P | Feb.-Apr. (Q) | Blade of 3rd leaf from apex | Optimum P%=0.16 | Craig, 1941 |

| Plant | Element | Time or stage of development | Part of plant | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference |
|---|---|---|---|---|---|
| SUGAR CANE (*Saccharum officinarum*) [*see also* Table X]—continued | | | | | |
| | P | Jan.-Apr. (Q) (5-6 months) | Blade of 3rd leaf from apex | Optimum P%=0.16-0.18 (M) | Craig & Halais, 1944 |
| | P | ——— | Leaf sheaths from elongating cane | P% adequate for maximum yield =0.08 (J) | Clements & Kubota, 1943; Clements *et al.*, 1945 |
| | P | Harvest | Stems (A) | Reduction in yield when P%<0.017 (I) | Borden, 1936a |
| | K | ——— | 3rd leaf from apex | Response to K fertilizer treatment when K%<1.25 | Craig, 1940 |
| | K | Feb.-Apr. (Q) | 3rd leaf from apex | Optimum K%=1.81 | Craig, 1941 |
| | K | ——— | Sheaths of elongating cane | K% adequate for maximum yield =2.25 (J) | Clements & Kubota, 1943; Clements *et al.*, 1945 |
| | K | Jan.-Apr. (Q) (5-6 months) | Blade of 3rd leaf from apex | Optimum K%=1.83-2.08 (M) | Craig & Halais, 1944 |
| | K | Harvest | Stems (A) | K supply inadequate when K%<0.20 (I) | Holmes, 1939 |
| SUGAR MAPLE (*Acer saccharum*) | | | | | |
| | N | Near end of season | Leaves | Optimum N%=2.77-2.85 | Mitchell & Chandler, 1939 |
| TOMATO (*Lycopersicum esculentum*) | | | | | |
| | N | Plant 12" high | Mature petioles (C) | Optimum $NO_3$-N%=0.10-0.15 (G) | Emmert, 1935a |
| | N | During fruit set | Mature petioles (C) | Optimum $NO_3$-N%=0.07-0.08 (G) | Emmert, 1935a |
| | N | Ripening | Mature petioles (C) | Optimum $NO_3$-N%=0.030-0.035 (G) | Emmert, 1935a |
| | N | Before fruit set | Mature petioles (C) | Optimum N%=0.15-0.20 (G) | Emmert, 1941 |
| | N | Between setting of 1st & 4th trusses | Mature petioles (C) | Optimum N%=0.10 (G) | Emmert, 1941 |
| | N | From 4th truss to final ripening | Mature petioles (C) | Optimum N%=0.20-0.25 (G) | Emmert, 1941 |
| | N | Final ripening | Mature petioles (C) | Optimum N%=0.10 (G) | Emmert, 1941 |
| | N | Before fruit set | Mature petioles (C) | Optimum N%=0.15 (G) | Emmert, 1942a |
| | N | During fruit set | Mature petioles (C) | Optimum N%=0.05-0.08 (GK) | Emmert, 1942a |
| | N | During fruit set | Mature petioles (C) | Optimum N%=0.08-0.15 (GL) | Emmert, 1942a |
| | N | Ripening | Mature petioles (C) | Optimum N%=0.05-0.10 (G) | Emmert, 1942a |
| | N | ——— | Stems (D) | Healthy when $NO_3$-N%=0.008-0.249 (G) | Hester, 1941 |
| | P | Plant 12" high | Mature petioles (C) | Optimum $PO_4$-P%=0.02-0.03 (G) | Emmert, 1935a |
| | P | During fruit set | Mature petioles (C) | Optimum $PO_4$-P%=0.035-0.040 (G) | Emmert, 1935a |
| | P | Ripening | Mature petioles (C) | Optimum $PO_4$-P%=0.030-0.035 (G) | Emmert, 1935a |
| | P | Before fruit set | Mature petioles (C) | Optimum P%=0.010-0.015 (G) | Emmert, 1941 |
| | P | During fruit set | Mature petioles (C) | Optimum P%>0.020 (G) | Emmert, 1941 |
| | P | Before fruit set | Mature petioles (C) | Optimum P%>0.02 (G) | Emmert, 1942a |

| Plant | Element | Time or stage of development | Part of plant. | Performance of plant as related to percentage of element (in dry matter, unless otherwise stated). | Reference. |
|---|---|---|---|---|---|
| TOMATO (*Lycopersicum esculentum*)—continued | | | | | |
| | P | During fruit set | Mature petioles (C) | Optimum P% > 0.04 (G) | Emmert, 1942a |
| | P | ———— | Stems (D) | Healthy when P% = 0.0043-0.0086 (G) | Hester, 1941 |
| | K | ———— | Stems (D) | Optimum K% = 0.166-0.249 (G) | Hester, 1941 |
| | K | ———— | Plant (?) | "Critical percentage" (see pp. 57, 58) of K = 0.9 | Macy, 1936; data from Hoagland & Martin, 1933 |
| | Mg | Mid-season | Leaves from mid-stem region | Mg supply inadequate when Mg% < 0.30 | Jones *et al.*, 1945 |
| TREMBLING ASPEN (*Populus tremuloides*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.64-2.77 | Mitchell & Chandler, 1939 |
| WHEAT (*Triticum vulgare*) | | | | | |
| | P | Harvest | Straw | Consistent response to P fertilizer treatment when P% < 0.07 | Wagner, 1915 |
| | P | Harvest | Straw | P supply adequate when P% > 0.065 | Jakuškin, 1915 |
| | P | Harvest | Straw | P supply almost certainly inadequate when P% < 0.03-0.04 | Jakuškin, 1915 |
| | K | Harvest | Straw | Consistent response to K fertilizer treatment when K% < 0.56 | Wagner, 1915 |
| | K | Harvest | Straw | Response to K fertilizer treatment when K% < 0.83 | Hoffmann, 1917 |
| | Cu | 6-8 weeks | Leaves | Cu supply highly inadequate when Cu% < 0.0003 | Teakle, 1942 |
| | Cu | 6-8 weeks | Leaves | Cu supply adequate when Cu% = 0.0007-0.0012 | Teakle, 1942 |
| WHITE ASH (*Fraxinus americana*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.80-2.86 | Mitchell & Chandler, 1939 |
| | N | Near end of season | Leaves | Cannot compete effectively when N% < 2.01 | Mitchell & Chandler, 1939 |
| WHITE OAK (*Quercus alba*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.72-2.80 | Mitchell & Chandler, 1939 |
| WHITE PINE (*Pinus strobus*) | | | | | |
| | N | Seedling stage | Plant | Optimum N% = 3.0 | Gast, 1937 |
| YELLOW POPLAR (*Liriodendron tulipifera*) | | | | | |
| | N | Near end of season | Leaves | Optimum N% = 2.97-3.02 | Mitchell & Chandler, 1939 |
| | N | Near end of season | Leaves | Cannot compete effectively when N% < 2.15 | Mitchell & Chandler, 1939 |

TABLE XII NOTES.

*N.B.—Notes A–D refer to column 4, E–P and R–T to column 5 and Note Q to column 3.*

(A) Expressed sap.
(B) Hot water extract.
(C) 2% acetic acid extract.
(D) Acetate buffer extract.
(E) If ratio $N/P_2O_5 > 2$.
(F) With high Na supply.
(G) % of fresh material.
(H) Read from graph.
(I) % in sap.
(J) On basis of sugar-free dry weight
(K) If P content (in the same terms) < 0.02
(L) If P content (in the same terms) > 0.02
(M) Varieties BH 10/12 and Big Tanna.
(N) If N % > 1.12-1.24
(O) Under long-day conditions.
(P) Under short-day conditions.
(Q) In Southern Hemisphere.
(R) With high carbohydrate content.
(S) With unfavourable weather conditions.
(T) With favourable weather conditions.

Interpretation Based on Nutrient Ratios.—Many investigators have not regarded the content of nutrient in the plant material as a suitable index on which to base diagnoses of nutritional status, but have preferred to compute the ratios of certain nutrients within the plant for diagnostic purposes. This procedure involves certain hidden assumptions about the form of the curves relating plant development to nutrient content. Let us suppose a three-dimensional figure in which the vertical axis represented whatever feature of development was being measured (say, the response to a particular fertilizer application) while the two horizontal axes represented the content of the two nutrients in question in the plant material, all other factors being held constant ; if development of the plant depends on the ratio of the two nutrients within it, and not on their individual values, then any vertical plane through the origin must cut the figure in a horizontal line. This has never been demonstrated. Gregory, in fact, was able in his experiments with barley to shew that when the supply of nitrogen and phosphorus increased in proportion (' balanced ' series) the ratio of these two elements within the plant remained constant (range of mean ratios $N/P_2O_5$ in the whole plant up to the fifth harvest 3.35—3.80) although their concentrations individually increased, and yields rose (see Table III). Moreover, where luxury consumption occurs it is clear that an increase in the supply of the nutrient in excess may increase the ratio of its internal concentration to that of the " limiting " nutrient without affecting either the internal concentration of the latter or the yield.

It is not to be denied that the ratios of nutrients within the plant may sometimes give useful indications as a supplement to those derived from the actual concentrations—though no information that could not be obtained from a curvilinear multiple regression—, but to use such ratios without consideration of the individual concentration data is, in most cases, unjustified (c.f. Richards, 1944).

Most investigators who have proposed ratios between nutrients as criteria for diagnostic purposes have made no attempt to justify their use as against percentages of the individual nutrients—and their data often shew that the latter are at least as good an index as the proposed ratio. Münter (1919), for instance, stated that wheat was deficient in nitrogen if the $\frac{P_2O_5}{N}$ ratio in the straw was greater than 0.6, but his figures shew that the correlation of yield increment due to nitrogen-containing fertilizer with this ratio was only +0.2969, while that with the percentage nitrogen content of the straw was —0.6375. Beauchamp and Lazo (1938) considered the ratio $\frac{K_2O}{N + P_2O_5}$ in the alcohol extract of sugar cane leaves to be a better index of the performance of the cane in the field under varying conditions of potassium nutrition than the content of potash alone ; if correlations are worked out between the yield increments with potassium-containing fertilizers and the values of these two indices, his data shew that while the correlation with the ratio is rather higher (the coefficients are —0.4521 and —0.4150 respectively), the difference is very small and both correlations are in any case non-significant owing to the small number of plots studied. Richards (1944) pointed out that the results of Hunter *et al.* (1943) on the calcium and potassium nutrition of lucerne are explained quite as well on the basis of the percentages of these two cations individually in the plant as by their ratio.

Lundegårdh (1934, 1935, 1939) claimed to have found that the ratio of potassium to calcium in oat leaves should lie between 1.5 and 5.0 for healthy development ; values outside these limits predisposed the plant to the development of grey speck disease, also associated with manganese deficiency. Samuel and Piper (1929) had concluded that manganese deficiency alone was responsible, the limiting value being 14 p.p.m. manganese in the plant dry matter (see Table II) ; this Lundegårdh (1931, 1932) could not accept, since some of his oat plants in solution culture remained healthy, though containing less than 1 p.p.m. manganese (see also data in Table I). That manganese deficiency was in some way connected with the disorder he could not deny, since affected plants generally contained less manganese than healthy plants from the same field ; but he also observed a correlation (though far from perfect) with the ratio mentioned. There would appear to be here a *prima facie* case for the diagnostic importance of a nutrient ratio, but further investigation is needed.

Stanford and his collaborators (1942) investigated potassium deficiency in maize, and computed the ratio $\frac{Ca + Mg}{K}$ within the plant (nutrient content being expressed as equivalents) as a diagnostic index They stated that all plants in which the ratio was less than 3.5 were normal, while those in which it exceeded 5.0 shewed more or less severe potash deficiency symptoms. Their paper does not make it too clear which of the plants studied were shewing symptoms, but, if in their Table II it is taken that all the plants from "unproductive" or "high lime" soil were shewing symptoms while the others were not, the ranges of potassium content are respectively 0.88—1.37 and 1.99—4.54 % in the dry matter, while the corresponding ranges for the ratios are 3.87—8.18 and 0.64—2.33—hardly a striking demonstration of the superiority of the latter as a diagnostic index.

Boresch (1938) investigated chloride injury of red currants—which was not always clearly distinguishable from potassium deficiency. He found no close relationship between the incidence of chloride injury and the chlorine content of the leaves—healthy leaves, for instance, might have as much as 1.9%, and affected leaves 1.4% or less—but there was a close relationship with the ratio of potassium to chlorine in the leaves, all injured leaves having values less than unity (content expressed in terms of equivalents) and all healthy leaves higher values. This did not include true potassium deficiency, symptoms of which appeared when the potassium content itself fell below a certain limiting value (see Table II), and was independent of the chlorine content. These results of Boresch on chlorine injury seem to provide an authentic instance of a nutrient ratio being of diagnostic importance.

Somers and Shive (1942) claimed to have shewn that the incidence of symptoms of iron or manganese deficiency in soybeans grown in solution culture was due solely to the ratio of these elements within the plant and thus that these symptoms could equally well be regarded as due to excess of the other element. But their figures indicate that the content of manganese alone is at least as good an index of the incidence of symptoms as the ratio of iron to manganese, as shewn in the table below :—

**Table XIII**

**Relation of manganese deficiency and toxicity symptoms in soybean to composition of leaves and roots (from Somers and Shive, 1942).**

| | Symptoms of manganese deficiency (or excess iron) | Normal | Symptoms of excess manganese* (or iron deficiency) |
|---|---|---|---|
| Ratio $\frac{\text{soluble† iron}}{\text{soluble† manganese}}$ in leaves | 4.47— 9.88 | 1.50— 2.65 | 0.58— 1.00 |
| p.p.m. soluble† manganese in leaf dry matter | 9.2 —10.8 | 15.5 — 28.6 | 36.3 — 83.6 |
| p.p.m. insoluble† manganese in leaf dry matter | 1.7 — 2.6 | 13.6 —102.4 | 173.4 —999.0 |
| Ratio $\frac{\text{soluble† iron}}{\text{soluble† manganese}}$ in roots | 12.4 —17.4 | 2.24— 5.04 | 1.17— 1.77 |
| p.p.m. soluble† manganese in root dry matter | 17.3 —18.9 | 24.3 — 43.1 | 48.8 —149.6 |
| p.p.m. insoluble† manganese in root dry matter | 0 | 0 — 49.4 | 61.6 —168.1 |

*Excluding one culture (No. 3), which shewed slight symptoms of manganese toxicity, although the composition fell within the normal range consistently on every criterion used.

†By "soluble" and "insoluble" are meant the fractions of the elements found in the expressed sap and in the press cake.

The data of Kriel (1941), quoted by Bennett (1945), indicate that in tomato chlorosis is not related, within a wide range, to the manganese content of the leaves ; nor is it at all consistently related to the ratio of the internal concentrations of iron and manganese. There seems, however, no doubt that the content of manganese in the plant and the incidence of symptoms depend upon the ratio of the concentrations of iron and manganese in the external solution, antagonistic phenomena possibly being involved.

Boron deficiency or toxicity symptoms have likewise been said to depend upon the ratio of calcium to boron in the plant rather than on the actual boron content (see Table XIV) In tobacco the ratio would appear to be a better nutritional index than the boron content of the material, though in the data for oats and soybeans there seems to be no reason to prefer one to the other.

**Table XIV**

**Relation of boron deficiency and toxicity symptoms to plant composition.**

| | Symptoms of boron deficiency | Normal | Symptoms of boron toxicity |
|---|---|---|---|
| *Tobacco* (*Drake et al.*, 1941) | | | |
| p.p.m. boron in plant dry matter | 4—5 | 4—5 | —— |
| Ratio calcium/boron in plant | 1500—2100 | 1275—1340 | —— |
| *Tobacco* (*Jones and Scarseth*, 1944)* | | | |
| p.p.m. boron in plant dry matter | —— | 18—32 | 23—176 |
| Ratio calcium/boron in plant | —— | 1302—1690 | 183—1009 |
| *Oats* (*Jones and Scarseth*, 1944) | | | |
| p.p.m. boron in plant dry matter | —— | 15—50 | 44—400† |
| Ratio calcium/boron in plant | —— | 170—780 | 17—282 |
| *Soybeans* (*Cook & Millar*, 1940; *Muhr*, 1941.) | | | |
| p.p.m. boron in plant dry matter | —— | 45—60† | 75—100 |
| Ratio calcium/boron in plant | —— | 53—359† | 114—191 |

*Statement as to incidence of symptoms somewhat ambiguous.
†Including plants with slight toxicity symptoms.

There is no reason to suppose that ratios in general are likely to be of greater use in diagnostic work than the content of the elements individually. This is not to deny that diagnosis of the nutritional status in respect of one element on a basis of its concentration in the plant may not need modification according to the level found for another element ; Lundegårdh has shewn conclusively (1941) that this is sometimes the case. But the computation of ratios is not in general the best way of making allowance for such effects, and its adoption as a general practice may well obscure relationships which otherwise would be patent.

Among the nutrient ratios which have been used from time to time as diagnostic criteria may be mentioned that of nitrogen to phosphorus, which has been used as an index of both nitrogen and phosphorus deficiency in oat grain (Atterberg, 1888a, 1889 ; Stahl-Schröder, 1904), barley straw (Godlewski, 1901), potato tubers (Godlewski, 1901), wheat straw (Münter, 1919), beet tops and roots (Münter, 1920), apple leaves and wood (Thomas and Anthony, 1927), grape-vine wood (Vinet, 1932a, 1933, 1934, 1935, 1937, 1938), cacao leaves (McDonald, 1935 ; McDonald and Rodriguez, 1935), grapefruit leaves (Hardy and Rodriguez, 1935) ; and pine seedlings (Gast, 1937) ; that of potassium to nitrogen, used as an index of potassium nutrition by Münter (1919, 1920) in wheat straw and beet tops and roots, by Gast (1937) in pine seedlings and by the Trinidad investigators (Hardy, 1937 ; Hardy and Rodriguez, 1935 ; McDonald, 1933, 1935 ; McDonald and Rodriguez, 1935) for leaves of cacao and grapefruit, and as an index of nitrogen nutrition by Godlewski (1901) in potato tubers ; that of potassium to phosphorus, used as an index of potassium nutrition by Godlewski (1901) in barley straw and potato tubers, by Beauchamp *et al.* (1934,

1935) in sugar cane leaves and by McDonald and Rodriguez (1935) in cacao leaves, and for both potassium and phosphorus nutrition in vine leaves by Herschler (1933) ; that of potassium to calcium as an index of deficiency of the former in barley straw (Godlewski, 1901), grapefruit leaves (Hardy and Rodriguez, 1935 ; Hardy *et al.*, 1935) ; and other types of sample (Bower and Pierre, 1944) ; that of potassium to magnesium for potassium deficiency in barley straw (Godlewski, 1901) ; that of nitrogen to silicon in wheat straw for nitrogen deficiency (Münter, 1919) ; and that of copper to nitrogen in pear leaves for copper deficiency (Oserkowsky and Thomas, 1938) Sometimes more complex ratios have been suggested ; for instance, Beauchamp and his colleagues (Beauchamp *et al.*, 1934, 1935 ; Beauchamp and Lazo, 1938) considered the ratio of potassium to the sum of nitrogen and phosphorus (as pentoxide) a good index of potassium deficiency in sugar cane leaves, and he later (1942) suggested the ratio of potassium to the sum of calcium and magnesium oxides for the same purpose, similarly to Stanford *et al.* (1942) and Bower and Pierre (1944). Münter (1919) in wheat straw even used the proportion of potassium to the sum of nitrogen and the oxides of calcium and magnesium in this way. Menchikowsky and Puffeles (1935) suggested that the ratio of univalent to divalent cations in grapefruit leaves was of importance.

By far the most prolific writers who have concerned themselves with the ratios between the different nutrient elements in plant tissue have been those of the " foliar diagnosis " school. Their methods have already been briefly described (p. 41). The sum of the percentages of nitrogen, phosphorus (as $P_2O_5$) and potassium (as $K_2O$) in the plant material is found, and called the " quantity " or " intensity " of nutrition ; the percentages may then be recomputed as equivalents, and each of the three nutrients is expressed as a percentage of their sum, the three resulting figures forming the " NPK-unit ", " equilibrium " or " quality " index of nutrition. These latter values are generally plotted in trilinear co-ordinates (the distance of a point from the three sides of an equilateral triangle representing the proportion of each nutrient in the "NPK-unit "), and the displacement of any point from that representing the optimum (corresponding with a particularly good yield) indicates the particular type and extent of the nutritional "disequilibrium " from which the plant is suffering. Sometimes the " intensity " figure is adduced as reason for a modification in the deductions from the " NPK-unit ", but more often it is disregarded. Where calcium and magnesium are determined the values are used with those for potassium to form a " K-Ca-Mg unit " similar to the " NPK-unit " described above.

This " foliar diagnosis " work must be subject to much the same criticisms as other work involving the use of ratios ; unless it is demonstrated experimentally that the " NPK-unit " is related more closely to the growth and yield of the plant than the individual nutrient percentages from which it is derived the extra computational work it demands cannot be justified and it may even obscure nutritional relationships unnecessarily. Such a demonstration has never been made. It is true that, where the " intensity " is also quoted, no information is lost by expressing the results in the " NPK-unit " form, and if the " intensity " were used as a third dimension to the trilinear co-ordinates in which the " NPK-unit " is plotted (as suggested by Lagatu and Maume, 1934a) it might be possible to express all the relationships latent in the material. This, however, has never been done, and without an experimental demonstration it is difficult to believe that the method of expression used in " foliar diagnosis " is the best. The work of the " foliar diagnosis " school has had considerable influence, and among those workers who have sometimes expressed their results in the " foliar diagnosis " form are Beauchamp (1939, 1940, 1940a, 1942 ; Beauchamp and Alvarino, 1940), Clements *et al.* (1941) and Borden (1942, 1944). Craig (1938, 1939) also has expressed his results for nitrogen, potassium and phosphorus analyses of sugar cane leaves as percentages of their total, but using the percentage concentrations in the plant material instead of the equivalent concentrations. He claimed (1939) that the ratios computed in this way differed less between varieties grown under the same conditions than did the original percentage figures, and considered this an advantage.

In Table XV are listed values of the various ratios which have from time to time been proposed as " limiting " or " optimal " ; the optimal values quoted by the Pennsylvania workers are omitted because it is not claimed that they apply more widely than to the actual experiment and season under consideration.

**Table XV.**

**Standard ratios of nutrient content proposed in the literature.**

| Plant | Ratio | Stage of development. | Organ | Standard value | | Reference |
|---|---|---|---|---|---|---|
| BARLEY (*Hordeum vulgare*) | | | | | | |
| | $P_2O_5$ : N | Harvest | Straw | P inadequate | <1:5 | Godlewski, 1901 |
| | $K_2O$ : CaO | Harvest | Straw | K inadequate | <5:4 | Godlewski, 1901 |
| | $K_2O$ : $P_2O_5$ | Harvest | Straw | K inadequate | <5:2 | Godlewski, 1901 |
| | $K_2O$ : MgO | Harvest | Straw | K inadequate | <5:1 | Godlewski, 1901 |
| COTTON (*Gossypium* spp) | | | | | | |
| | Ca : (K+Na) | Aug. | Plant | Optimum | <1:1 (A) | Cooper & Garman, 1943 |
| GRAPE (*Vitis vinifera* etc). | | | | | | |
| | N : $P_2O_5$ : $K_2O$ | Mean of several successive samples. | Basal leaves of fruiting shoots | Optimum | =41:8:51 | Lagatu, 1940 ; Lagatu and Maume, 1936a, 1936e, 1938, 1938b, 1938c |
| | N : $K_2O$ | June-July | Basal leaves of fruiting shoots | Optimum | =4:5 | Lagatu, 1940 |
| | $K_2O$ : $P_2O_5$ | Autumn | Leaves | Normal | =2:1 | Herschler, 1933 |
| LUCERNE (*Medicago sativa*) | | | | | | |
| | Ca : K | ———— | Tops | Yield reduced | >4:1 (A) | Hunter *et al.*, 1943 ; Bear & Prince, 1945 |
| OATS (*Avena sativa*) | | | | | | |
| | N : $P_2O_5$ | Beginning of flowering | Tops | Optimum | =100:45 | Atterberg, 1889 |
| | N : $P_2O_5$ | Harvest | Grain | Optimum | =100:55 | Atterberg, 1889 |
| | N : $P_2O_5$ | Harvest | Grain | Optimum nutrient balance in soil | =100:35-40 | Stahl-Schröder, 1904 |
| | N : $K_2O$ | Harvest | Grain and straw respectively | Optimum | =1 : 1 | Atterberg, 1889 |
| POTATO (*Solanum tuberosum*) | | | | | | |
| | N : $P_2O_5$ : $K_2O$ | Harvest | Tubers | Normal | =10:8:3 | Godlewski, 1901 |
| | N : $P_2O_5$ : $K_2O$ | Mean of several successive samples | Basal leaves of primary shoots | Optimum | =38:4:58 | Lagatu & Maume, 1934c, 1935b |
| | N : $P_2O_5$ | Harvest | Tubers | N inadequate | <2:1 | Godlewski, 1901 |
| | N : $K_2O$ | Harvest | Tubers | N inadequate | <3:5 | Godlewski, 1901 |
| | $K_2O$ : $P_2O_5$ | Harvest | Tubers | K inadequate | <3:1 | Godlewski, 1901 |
| SCOTS PINE (*Pinus sylvestris*) | | | | | | |
| | N : P : K | Seedling | Plant | Normal | =100:12:35 | Gast, 1937 ; from data of Manshard, 1938 |
| SOYBEAN (*Glycine soja*) | | | | | | |
| | Ca : B | Harvest | Plant (?) | Optimum | =500 : 1 | Jones & Scarseth, 1944, from data of Muhr, 1941 |
| SUGAR BEET (*Beta vulgaris*) | | | | | | |
| | N : $P_2O_5$ | Harvest | Tops | N inadequate | <20:7 | Münter, 1920 |
| | $P_2O_5$ : N | Harvest | Tops | P inadequate | <1:5 | Münter, 1920, 1920a |
| | $P_2O_5$ : N | Harvest | Roots | P inadequate | <1:4 | Münter, 1920 |
| | $K_2O$ : N | Harvest | Leaves | K inadequate | <1:1 | Münter, 1920a |
| | $K_2O$ : N | Harvest | Roots | K inadequate | <17:20 | Münter, 1920 |
| | Ca : B | ———— | ———— | Optimum | =100:1 | Jones & Scarseth, 1944, from data of Cook & Millar, 1940 |
| SUGAR CANE (*Saccharum officinarum*) | | | | | | |
| | N : $P_2O_5$ : $K_2O$ | ———— | Third leaf blades from apex | Optimum | =50:12:38 | Craig, 1938 |
| | $K_2O$ : (N+$P_2O_5$) | 9 months | Leaves | Good growth | >2:1 (B) | Beauchamp *et al.*, 1934 |
| | $K_2O$ : $P_2O_5$ | 9 months | Leaves | Good growth | >3:1 (B) | Beauchamp *et al.*, 1934 |

| Plant | Ratio | Stage of development. | Organ | Standard value | | Reference |
|---|---|---|---|---|---|---|
| TOBACCO (*Nicotiana tabacum*) | | | | | | |
| | N : K | ——— | Cured leaves | Optimum | =8-11:10 | Gribbins *et al.*, 1941 |
| | K : Mg | ——— | Leaves | Optimum quality | =59:10 | Drake & Scarseth, 1940 |
| | Ca : B | Flowering (?) | Plant (?) | Normal | <1340:1 | Drake *et al.*, 1941 |
| | Ca : B | Flowering (?) | Plant (?) | Optimum | =1200:1 | Jones & Scarseth, 1944, from data of Drake *et al.*, 1941 |
| WHEAT (*Triticum vulgare*) | | | | | | |
| | $N : P_2O_5$ | Harvest | Straw | N inadequate | <5 : 3 | Münter, 1919 |
| | $N : SiO_2$ | Harvest | Straw | N inadequate | <3:50 | Münter, 1919 |
| | $P_2O_5 : N$ | Harvest | Straw | P inadequate | <7:20 | Münter, 1919 |
| | $K_2O : N$ | Harvest | Straw | K inadequate | <2:1 | Münter, 1919 |
| | $K_2O$ : (N+CaO+MgO) | Harvest | Straw | K inadequate | <1:1 | Münter, 1919 |

NOTES: A. Calculated as equivalents.
B. In alcohol extract.

Where optimal values for nutrient content or ratios of nutrients in the plant have been determined, it is possible, instead of attempting to forecast the yield increment to be expected from a given application to plants with a given nutrient content, to proceed by trial and error. That is, an arbitrary amount of fertilizer is applied, and if this fails to raise the nutrient content to the optimum a further application is made. This procedure has been recommended by the "foliar diagnosis" school (see p. 41) and by Yuen and Hance (1939) among others. It is, however, uneconomic, since in the region immediately below the optimum yield rises only slowly with the increasing nutrient supply and internal concentration; consequently this method of using plant analyses as a guide to fertilizer treatment can only be recommended where the cost of the latter forms no more than a very small proportion of the value of the crop.

INTERPRETATION BASED ON COMPARISON OF GOOD AND BAD PLANTS FROM THE SAME FIELD OR PLANTATION.--Many investigators have attempted to avoid the necessity of setting up standard values, curves or ratios for plant composition by confining their comparisons to those between "good" and "bad" plants growing in the same field or plantation (Joulie, 1876; Stahl-Schröder, 1904; Hester 1941, etc.). This procedure is subject to the objection that, without knowledge of the effect of treatments on the plants, it is impossible to be sure whether any differences in composition are causes, effects, or merely concomitants of the differences in growth or appearance of the plant (c.f. Lilleland and Brown, 1940; Guest, 1943). This is true even where it is possible to demonstrate (as suggested by Chapman, 1941) a correlation between plant growth and the content of a particular nutrient. This comparison of "good" and "bad" plants is virtually the only means of attacking by plant analysis the problem of the etiology of unidentified physiological disorders (see p. 20), but it can in no way be regarded as a substitute for the establishment of standards for nutrient content.

## FACTORS AFFECTING THE USE OF PLANT ANALYSIS FOR DEFICIENCY DIAGNOSIS.

**Weather Conditions.**—There is abundant evidence that external factors other than nutrient supply affect the concentrations of the nutrient elements within the plant. Illumination, for instance, has been shewn to affect the phosphorus and potassium content of white pine seedlings (Mitchell, 1936) and the nitrate content of beet (R.I. agric. Exp. Sta., 1935) and cereals (Wark, 1938, 1939)—the latter to such an extent that only samples taken in bright weather were considered to give reliable diagnostic indications. Water supply or rainfall has often been shewn to affect nutrient content (Tollens, 1902; Pfeiffer *et al.*, 1912, 1913; Richards, 1932; Daniel and Harper, 1934; Beaumont and Snell, 1935; Emmert, 1936; Yates and Watson, 1939; Lilleland and Brown, 1941; Green, 1943) though it is often difficult to know to what extent this

effect may be due to greater amounts of nutrients being made available to the plant. The great variations in nutrient content of plants as a result of weather (see, for instance, Stahl-Schröder, 1904 ; Ames, 1910 ; Münter, 1919, 1920 ; Borden, 1936 ; Yates and Watson, 1939) are partly to be ascribed to direct effects of weather conditions on the plant, partly to their effect on the soil.

As already indicated (p. 60) the fact that environmental conditions cause alterations in the percentage nutrient content need in no way affect the course of analytical diagnosis, provided they do not also affect the relation between the increase in yield as a result of fertilizer treatment and plant composition. Though Pfeiffer *et al.* (1912) maintained that the percentage increase in yield with treatment corresponding to a given internal nutrient concentration was unaffected by external factors, there is some evidence that this is not strictly true (Stahl-Schröder, 1904 ; Ulrich, 1943 ; Thomas *et al.*, 1943a ; Boynton and Burrell, 1944 ; Hibon, 1944). Nevertheless Lundegårdh (1941) found his standard values applied tolerably well to different seasons ; as already shewn (p. 107) Münter's (1919, 1920) results from five consecutive and very different seasons give quite a good correlation between yield increase and nutrient percentage ; and the fact that Lagatu and Maume (see Table XV) have regarded their optimum composition for grape-vine leaves as applying to more than one season points in the same direction. Boynton and Compton (1945) report that seasonal differences in weather do not affect the relation between potassium and magnesium content of apple leaves and the incidence of deficiency symptoms, but that the optimum nitrogen content for fruit colour may differ with climate.

The most serious attempts to make allowance for such possible effects of weather differences have taken the form of trying to find some characteristic of the plant serving as an index of these differences, such as plant colour or sugar content (see p. 43) ; Emmert (1942), among others, has indicated the need for carbohydrate determinations. Clements and Kubota (1942) suggested determination of the water content of the sheaths surrounding the elongating part of the sugar cane as an index of moisture relations. Wark's (1938, 1939) avoidance of samples taken in dull weather has been mentioned ; likewise, Craig and Halais (1944) do not sample sugar cane leaves immediately after a drought or cyclone. Soulmagnon (1933) considered foliar diagnosis should be used only when water supplies were adequate. Yuen and Hance (1939) quote different critical values for the nitrogen content of sugar cane leaves under favourable and unfavourable weather conditions (see Table XII).

**Pests and Diseases.**—To the factors affecting the diagnostic use of plant analysis must probably be added pests and diseases. Though there is little experimental evidence on the subject, it would seem to be a sound principle to avoid sampling diseased plants (other than plants suffering from the nutritional disorder under investigation—see pp. 19-40, 69) for diagnostic purposes—even though nutrient deficiency may sometimes result in increased susceptibility to disease (Eaton, 1944). Likewise it is probably desirable to reject for purposes of determining standard values yield results derived from plants suffering to any marked extent from a pest or disease, and to make it clear that diagnostic conclusions only apply to otherwise normal and healthy plants.

**Fixation of Nutrients by the Soil.**—Differing fixation of nutrients by different soils is a factor which it is risky to neglect, and which can only be estimated—short of field or pot trials—by examination of the soil itself. Lundegårdh's (1934) original plan in his " Triple Analysis " method was to analyse the soil as well as the plant, which would have enabled him to allow for this factor ; later, however, he considered that the additional information given by soil analysis in respect of the three principal nutrients was insufficient to justify the additional labour. He found (1941) that his standard values applied equally well to soils of very different type.

**Variety.**—A factor to which little attention has been devoted in previous pages is the influence of variety in diagnostic work. There is abundant evidence that the differences in genetical constitution between varieties of cultivated plants may include differences affecting their mineral composition when grown under the same conditions—for instance in oats (Lundegårdh, 1931, 1932 ; Rademacher, 1937), apple (Wallace, 1931 ; Piper, 1936 ; Batjer and Magness, 1939), gooseberry (Wallace, 1931), tomato (Jones *et al.*, 1944), wheat (Tisdal, quoted by Lundegårdh, 1932 ; Maume and Dulac, 1934, 1935a, 1936, 1937, 1938, 1938a ; Maume and Bouat, 1937), sugar cane (Borden, 1936 ; Craig, 1938, 1939 ; Beauchamp and Alvarino 1940), grapefruit (Fudge, 1938, 1939), grape vine (Scott, 1941, 1944) and cotton (Crowther, 1936). Other workers have found only small or inconsistent differences in composition between varieties (Stahl-

Schröder, 1904 ; Poehlmann, 1935 ; Brandenburg, 1939 ; Yates and Watson, 1939 ; Lilleland and Brown, 1941, 1942 ; Carson *et al.*, 1941 ; MacVicar *et al.*, 1941 ; Batjer and Haller, 1942), but it seems clear that in many cases varietal differences are too large to be disregarded.

A variety used as a rootstock may not only differ in composition from other such varieties (Roach, 1930, 1931, 1933) but also affect that of the scion variety (Eaton and Blair, 1935 ; Vaidya, 1938 ; Lagatu and Maume, 1939 ; Goodall, 1945a ; Haas, 1945a).

If varieties differ not only in composition but also in potential fertilizer response corresponding to a particular mineral content, diagnosis will be seriously inconvenienced by the necessity for setting up separate standard values for each variety. It seems, however, that in many cases the varietal differences in composition represent simply differing ability to absorb nutrients from the substrate in question, and not differing reaction to a given internal concentration. Where this is true, or where the different composition is ascribable to some other non-nutritional difference between the varieties, such as the formation of seedless fruit (Fudge, 1938, 1939), standard values may apply without modification according to variety. Craig (1941) came to the conclusion that " no very great error will be introduced if " the same optimal values for nutrient concentrations in sugar cane leaves " are used for any of the varieties so far studied," though later he and Halais (1944) quoted different optima for different varieties, basing them simply on their differing leaf composition when the varieties were grown side by side. In some cases, however, the relation of plant development to internal nutrient concentration does indeed appear to differ from variety to variety. Wallace (1940), for instance, found the limiting value for magnesium deficiency in the apple to be different in Laxton's Superb from that in other varieties, and Ravikovitch and Bidner (1937) came to similar conclusions in regard to chloride injury of the grape vine. Walsh and Cullinan (1945) found that the differing susceptibility of pea varieties to manganese deficiency was not accompanied by any corresponding differences in manganese content. Lineberry and Burkhart (1943) found that in strawberry the calcium content of plants of the variety Klondike showing symptoms of calcium deficiency fell well within the normal range for the variety Blakemore (see Table I). Crowther (1936) found that the cotton variety Gisa 7 had a particularly high nitrogen content, yet responded as well to nitrogenous fertilizers as the other varieties studied. Emmert (1942a) found the optimal nitrogen content (2% acetic acid extract) in tomato petioles to be higher in restricted-vine varieties than in those of a free-vining habit. Nevertheless, a number of investigators have expressed the opinion that relationships between fertilizer response and plant composition will hold with little modification over wide groups of plants ; Lundegårdh (1941) considered that his results with oats would apply broadly to other cereals, Neller (1935) found similar optimal sap phosphorus concentrations in the various species with which he worked and Wallace (1941 ; Wallace and Osmond, 1941) stated that the limiting values for potassium and magnesium deficiency, which he had found in work mainly with the apple, could be extended very generally to other fruit plants. But the data in Tables, I, II, XII and XV bear eloquent witness to the fact that critical values cannot be expected to apply more widely than to a group of related plants unless some new and much more fundamental basis for expressing such values can be found.

**Fruiting.**—Differences in the bearing behaviour of fruit plants may be associated with considerable differences in the composition of the vegetative organs, on account of the heavy drain on the plant's nutrient reserves caused by fruit production. Such differences may even be apparent between different portions of the same plant (Lagatu and Maume, 1938c ; Fudge, 1938, 1939). Thomas (1945), on the other hand, found little difference between the composition of leaves from fruiting and non-fruiting shoots of apple trees. Where the cropping behaviour of a plant varies considerably from year to year, it is clear that its nutrient requirements over a period of years could not be satisfactorily predicted from analysis of samples taken in one year only, unless account were taken of the fruit actually borne in that year (Hoagland and Arnon, 1941). Lilleland (1933) has pointed out that uncertainty as to the crop to be borne by plum trees will interfere with use of analyses of leaves sampled early in the season for predicting the probability of leaf scorch later.

# THE PLACE OF PLANT ANALYSIS AMONG OTHER METHODS OF NUTRITIONAL DIAGNOSIS

## COMPARISON OF PLANT ANALYSIS WITH FIELD TRIALS AS A DIAGNOSTIC METHOD.

It has been stated that the field trial represents the ultimate test to which any other proposed method of nutritional diagnosis must be submitted. But as a diagnostic method the field trial is subject to a number of disadvantages. First : in its traditional form, the results cannot be used during the year in which it is set up ; this objection is met by some recent modifications (Evans, 1942 ; Wallace, 1943) in which observations are made at an early stage of development on some plant character, such as stem growth rate or leaf colour, which is correlated with final yield—but in such cases this correlation is the crucial, and sometimes doubtful, point. Second : its results are subject to substantial errors; in a properly designed trial these errors are random and at the cost of additional labour may be reduced to any extent desired. Third : it makes very heavy demands upon labour. Thus, while an extensive set of field trials is essential for standardising the results of other diagnostic techniques, it is very probable that when it is necessary to answer the question of what nutritional treatment is required by a crop about to be grown or already growing in a particular field, such other techniques may be more appropriate than an *ad hoc* field trial.

If plant analysis be considered against the background of these disadvantages of the field trial as a diagnostic method, it will readily be seen that in regard to labour costs, at least if the " capital expenditure " needed to set up standard values be disregarded, plant analysis is much to be preferred. Lindner (1944), for instance, reports that samples may be analysed for the five principal nutrient elements at the rate of two per hour, with a very satisfactory degree of chemical accuracy, and Wolf (1944a) quotes the figure of twenty-four samples analysed per day for three elements ; even if time is added for the collection and preparation of the samples it will be seen that the labour required is incomparably less than for field trials. To some of the methods for rapid testing of plant material in the field this applies with even greater force. The errors of diagnosis by plant analysis will not always be random, and cannot always, like those of field trials, be diminished indefinitely by increased replication—for the standard values or curves on comparison with which the diagnosis is based are necessarily themselves subject to error ; nevertheless an estimate by plant analysis based on standards derived from an extensive series of field trials may be nearer to the true yield response than an estimate derived from a field trial on the actual site (Lundegårdh, 1941 ; Thomas *et al.*, 1942). In respect of basal fertilizer dressings for annual crops, plant analysis may suffer from the same disadvantage as an *ad hoc* field trial—that results will only be available for subsequent crops, unless it is possible before planting time to obtain plant material (from weeds or from the previous crop) for which standard analytical values *in relation to the performance of the subsequent crop* are available. For top or side dressings to established plants, however, results of plant analysis may be put to immediate practical application, and it would be unnecessary, as with a field trial, to wait until the harvest had been completed before drawing conclusions. With perennial crops it may be necessary to carry a field trial on for several years before the full effect of the treatments can be seen, but plant analysis (given suitable standardization) can give an immediate forecast of the response to treatment. Some of the advantages of plant analysis in labour and time over *ad hoc* field trials would be lost if it were necessary to grow plants specially to provide the samples for analysis—as has been suggested for instance by Münter (1919, 1920, 1920a).

While plant analysis can often provide a sensitive index of the need for nutrients in relatively poor supply, it is rather insensitive to changes in the supply level of nutrients adequate in relation to other " limiting factors." Very generally speaking, the analysis of plants not receiving special treatments will often show only which nutrient is " limiting " (Wallace, 1928a ;

Thornton, 1932; Emmert, 1934; McDonald, 1934; Thornton *et al.*, 1934; Scarseth, 1941, 1941a; Ulrich 1944) and not those to which responses would be obtained if the supply of the "limiting" nutrient had been itself increased; sometimes, however (Carolus *et al.*, 1938; Wallace, 1943; Roberts, 1945) deficiency of more than one nutrient may be shewn simultaneously.

It must be remembered that, while plant analysis may provide a good index of the nutritional status of the plant, the response of the plant to fertilizer treatments applied to the soil will also depend upon the nature of the soil. This is clearly recognized by the "Foliar Diagnosis" school (Lagâtu and Maume, 1936e). Too much stress should not be laid upon this, for over a wide range of soils differences in nutrient fixation will not greatly affect the value of diagnosis by plant analysis—and will in any case only affect the extent of response, and not its existence or direction. Still, it seems probable that information about the soil would often prove a valuable means of correction to diagnoses derived from plant analysis.

## COMPARISON OF PLANT ANALYSIS WITH SOIL ANALYSIS AS A DIAGNOSTIC METHOD.

Soil analysis for diagnostic purposes, like plant analysis, represents a great saving in labour in comparison with field trials, and has the advantage over both methods that results may be obtained with very little delay at any time of the year. It has also the important advantage over plant analysis that it is equally sensitive to nutrients in relatively good and relatively poor supply. In comparisons of forecasts of fertilizer response by plant analysis and by soil analysis, it should be remembered that attention has been given continuously and on a wide scale over several decades to the development of methods of soil analysis and to their standardization against field trials, whereas the same can hardly be said of plant analysis. Nevertheless many investigators have in practice found plant analysis of greater value; this was Loehwing's (1928) view in his study of over-liming injury, and that of Emmert (1931) in his work on soil reaction, while Gilbert and Smith (1929) came to the same conclusion in regard to nitrogen nutrition of vegetable crops. Lundegårdh's (1934) method of "triple analysis" originally included analyses of soil and subsoil samples as well as of plant material; however, he found that very little information was lost by omitting the soil and subsoil analyses and so later confined his attention to the plant material. Lilleland and Brown (1941) found that effects of differing drainage on potassium nutrition of peach leaves were not revealed in soil analysis, but were clear from leaf analysis. Boynton (1942) found leaf analysis preferable for the diagnosis of potassium deficiency in fruit trees. Carolus *et al.* (1938) have pointed out that localized fertilizer applications may make it difficult to secure a representative soil sample, though in no way interfering with the use of plant analysis. Mitchell (1939) and Lundegårdh (1941) have drawn attention to the fact that plant analysis makes full allowance for the extent to which plant roots penetrate different soil horizons, whereas this can hardly be done in a technique of soil analysis alone. Among others who have compared soil and plant analysis techniques for the major nutrients, and found the latter often to be more useful are Liebscher *et al.* (1898), Ames (1910), Hester (1931) Sayre (1941), Scarseth (1943) and McCollam (1943). Diagnostic soil analysis for the trace elements has as yet been little developed, and here plant analysis appears to have an important role to play.

It has been suggested that a useful method of combining the techniques of soil and plant analysis would be to use soil analysis as a means of determining what basal fertilizer dressing should be applied before the crop is planted, and to use the results of subsequent periodical plant analysis to determine whether that basal dressing has been taken up by the crop, whether it has been adequate, and whether additional top or side dressings are needed.

## COMPARISON OF PLANT ANALYSIS WITH THE USE OF DEFICIENCY SYMPTOMS AS A DIAGNOSTIC METHOD.

The only important remaining method of deficiency diagnosis is by the visual recognition of symptoms. This is a very direct and rapid method, but the symptoms of a disorder are not always as definite and as characteristic as might be wished (see p. 10). Confirmation that an abnormality is symptomatic of deficiency of a specific element is very desirable, and for this purpose the method of injection developed by Roach (see p. 8) seems particularly appropriate. In certain cases proof of a definite deficiency has been established beyond doubt by this method,

but in this connection further work requires to be done to determine the factors affecting response and the physiological changes accompanying the re-establishment of normal appearance of the leaves.

Where symptoms can be readily and definitely recognized this is probably the ideal method of diagnosis ; but there is always the likelihood that, if the deficiency could have been identified and remedied before symptoms appeared, the final yield might have been higher than if treatment had to wait upon the recognition of symptoms. Furthermore there is abundant evidence that nutrient deficiencies not severe enough to produce recognizable symptoms cause a reduction in growth and yield though the same does not appear to be equally true of toxicity effects (Scofield and Wilcox, 1931 ; Eaton, 1944). It is in such cases of less severe deficiency (Lagatu and Maume, 1935e ; Cullinan and Batjer, 1943 ; Lindner, 1944), and to indicate deficiency at an earlier stage than symptoms can be expected to appear (MacGillivray *et al.*, 1930 ; Hardy, 1937 ; Olson, 1942a ; Green, 1943 ; Scarseth, 1943 ; Large, 1944, 1945), that plant analysis is likely to be a valuable supplement to the observation of deficiency symptoms. The use of plant analysis in confirming uncertain diagnoses based on symptoms or the results of injection cannot be questioned apart from its use in the many cases where no characteristic symptoms appear at all.

It thus appears that when a satisfactory technique has been worked out according to the principles set out in preceding sections, and standard values have been firmly based upon an extensive series of field trials, plant analysis should be of great value in combination with soil analysis, particularly for perennial crops and to indicate the need of annual crops for fertilizer treatments subsequent to planting time. While in many cases neither plant nor soil analysis can compete in ease and rapidity with the identification of symptoms of nutritional disorders as a means of diagnosis, they provide the possibility of preventing the appearance of such symptoms. Besides this use of plant analysis in what may broadly be termed advisory work, it can be very useful too in interpreting the results of fertilizer trials and in finding the cause of physiological disorders of unknown origin (see p. 20). But in the more practically important field of advisory work the great importance of care in selecting a technique and in the determination of standard values cannot be too strongly emphasized.

# BIBLIOGRAPHY


ACOCK, A. M. 1941. An examination of Mulder's rapid biological method for estimating the amount of available copper in soils. *J. Coun. sci. industr. Res. Aust.* 14, 288-300.

AIYAR, S. P. 1945. A chlorosis of paddy (*Oryza sativa L.*) due to sulphate deficiency. *Curr. Sci.*, 14, 10-11.

ALBEN, A. O., and HAMMAR, H. E. 1940. Phosphorus content of some south-western pecan soils and influence of phosphate fertilizers on pecan foliage. *Proc. Soil Sci. Soc. Amer.*, 4, 173-176.

ALBERT, W. B. 1932. Further observations on manganese deficiency in soils at Florence. *Rep. S.C. agric. Exp. Sta. for* 1931-2, 45, 46.

ALBRECHT, W. A. 1943. Potassium in the soil colloid complex and plant nutrition. *Soil Sci.*, 55, 13-21.

ALDRICH-BLAKE, R. N. 1930. The plasticity of the root system of Corsican pine in early life. Researches designed to facilitate the establishment of this tree in Great Britain. *Oxf. For. Mem.*, 12, 1-64.

ALWAY, F. J. 1928. Detection of sulfur-deficiency of soils by means of plants. *1st Int. Congr. Soil Sci*, 3, 590-618.

———, SHAW, W. M., and METHLEY, W. J. 1926. Phosphoric-acid content of crops grown upon peat soils as an index of the fertilization received or required. *J. agric. Res.*, 33, 701-740.

AMES, J. W. 1910. The composition of wheat. Influence of various factors on the phosphorus, potassium and nitrogen content of the wheat plant. *Bull. Ohio agric. Exp. Sta.*, 221, 1-37.

——— and GERDEL, R. W. 1927. Potassium content of plants as an indicator of available supply in the soil. *Soil Sci.*, 23, 199-223.

ANDERSON, M. S., and NOBLE, W. M. 1937. Comparison of various chemical quick tests on different soils. *Misc. Publ. U.S. Dep. Agric.*, 259, 1-23.

ANDERSSEN, F. G. 1932. Chlorosis of deciduous fruit trees due to a copper deficiency. *J. Pomol.*, 10, 130-146.

ARCHIBALD, E., and WANN, F. B. 1942. The zinc content of " little-leaf " and normal leaves. *Amer. J. Bot.*, 29, 694.

ARND, T., and HOFFMANN, W. 1937. Spurenelemente und ihre Wirkung auf das Pflanzenwachstum unter besonderer Berücksichtigung von Versuchsergebnissen mit Kupfer. *Landw. VersSta.*, 129, 71-99.

ARNON, D. I. 1943. Mineral nutrition of plants. *Ann. Rev. Biochem.*, 12, 493-528.

ASKEW, H. O. 1935. The boron status of fruit and leaves in relation to " internal cork " of apples in the Nelson district. *N.Z.J. Sci. Tech.*, 17, 388-391.

——— 1944. A case of combined potassium and boron deficiencies in grapes. *N.Z.J. Sci. Tech., A*, 26, 146-152. *Better Crops with Plant Food*, 29 (5), 21-24, 44-46.

——— and CHITTENDEN, E. 1936. The use of borax in the control of " internal cork " of apples. Part II. The effect of tree injection of borax solutions on the boron status of apple trees. *J. Pomol.*, 14, 239-242. *N.Z.J. Sci. Tech.*, 18, 376-378.

——— ——— 1936a. The use of borax in the control of " internal cork " of apples. Part III. Effect of borax sprays on the boron status of fruit and incidence of " internal cork " in apples. *J. Pomol.*, 14, 242-245. *N.Z.J. Sci. Tech.*, 18, 378-380.

———, ———, and THOMSON, R. H. K. 1936. The use of borax in the control of " internal cork " in apples. Part I. The influence of borax top dressing on the boron status of soil, fruit and leaves. *J. Pomol.*, 14, 228-239. *N.Z.J. Sci. Tech.*, 18, 366-376.

——— and THOMSON, R. H. K. 1937. Occurrence of internal cork of apples in Central Otago, New Zealand. *N.Z.J. Sci. Tech.*, 18, 661-664.

ASKEW, H. O., and THOMSON, R. H. K. 1939. Boron status of New Zealand apples. *N.Z.J. Sci. Tech.*, 21, 128A-129A.
———— and WILLIAMS, W. R. L. 1939. Brown-spotting of apricots, a boron-deficiency disease. *N.Z.J. Sci. Tech.*, 21, 103A—106A.
ATKINSON, H. J., PATRY, L. M., and WRIGHT, L. E. 1944. Plant tissue testing. *Sci. Agric.*, 24, 437-442.
ATTERBERG, A. 1886. Die Beurtheilung der Bodenkraft nach der Analyse der Haferpflanze. *Landw. Jb.*, 15, 415-419.
———— 1887. Die Beurtheilung der Bodenkraft nach der Analyse der Haferpflanze II. *Landw. Jb.*, 16, 757-761.
———— 1887a. *Kalmar Kem. Sta. Årsberätt.* [quoted by Atterberg (1901)].
———— 1887b. *LandbrAkad. Tidskr.* [quoted by Atterberg (1901)].
———— 1888. *Kalmar Kem. Sta. Årsberätt.*, 22-28. [quoted by Helmkampf (1892); Atterberg (1901)].
———— 1888a. *Kalmar Kem. Sta. Tio-årsberätt.* 1877-1887, Beil. 2, 13. [Quoted by Helmkampf (1892).]
———— 1889. *Kalmar Kem. Sta. Årsberätt.*, 47-54. [Quoted by Helmkampf (1892); Atterberg (1901)].
———— 1901. Die Variationen der Nährstoffgehalte bei dem Hafer. *J. Landw.*, 49, 97-172.
AYERNA-SACCÁ, R. 1912. A chlorose da laranjeira e de outras plantas nas terras ferruginosas. *Bol. Agric. S. Paulo*, 13, 129-150.
BAHRT, G. M., and HUGHES, A. E. 1937. Soil fertility and experiments on bronzing of citrus. *Proc. Fla hort. Soc.*, 50, 23-28.
BAKER, C. E. 1936. The relation of nitrogen and soil moisture to growth and fruitfulness of apple trees under different systems of soil management. *Bull. Ind. agric. Exp. Sta.*, 414, 1-36.
———— 1941. The effect of different methods of soil management upon the potassium content of apple and peach leaves. *Proc. Amer. Soc. hort. Sci.*, 39, 33-37.
———— 1943. Further results on the effect of different mulching treatments upon the potassium content of apple leaves. *Proc. Amer. Soc. hort. Sci.*, 42, 7-10.
BALMUKAND, B. 1928. Studies in crop variation. V. The relation between yield and soil nutrients. *J. agric. Sci.*, 18, 602-627.
BARTHOLOMEW, R. P., and JANSSEN, G. 1929. Luxury consumption of potassium by plants and its significance. *J. Amer. Soc. Agron.*, 21, 751-756.
————, WATTS, V. M., and JANSSEN, G. 1933. The effect of variations in the nutrient media upon the nitrogen, phosphorus, and potassium content of plants with special reference to the tomato. *Bull. Axk. agric. Exp. Sta.*, 288, 1-42.
BATHURST, A. C. 1943. New method for estimating the fertilizer requirements of citrus trees. *Fmg. S. Afr.*, 18, 323-327. *Citrus Leaves*, 23 (ii), 8-9, 22.
———— 1944. Leaf analysis of citrus. *Fmg. S. Afr.*, 19, 325-328.
———— 1944a. Method of sampling citrus leaves for diagnosis purposes. *Fmg. S. Afr.*, 19, 329-330.
BATJER, L. P., and DEGMAN, E. S. 1940. Effects of various amounts of nitrogen, potassium, and phosphorus on growth and assimilation in young apple trees. *J. agric. Res.*, 60, 101-116.
———— and HALLER, M. H. 1942. Fruit maturity and growth of apple trees as affected by boron content (preliminary report). *Proc. Amer. Soc. hort. Sci.*, 40, 29-30.
———— and MAGNESS, J. R. 1939. Potassium content of leaves from commercial apple orchards. *Proc. Amer. Soc. hort. Sci.*, 36, 197-201.
BAULE, B. 1918. Zu Mitscherlichs Gesetz der physiologischen Beziehungen. *Landw. Jb.* 51, 363-385.
BAVER, L. D., and BRUNER, F. H. 1939. Rapid soil tests for estimating the fertility needs of Missouri soils. *Bull. Mo. agric. Exp. Sta.*, 404, 1-16.
BEAR, F. E., and PRINCE, A. L. 1945. Cation-equivalent constancy in alfalfa. *J. Amer. Soc. Agron.*, 37, 217-222.

BEATH, O. A., GILBERT, C. S., and EPPSON, H. F. 1939. The use of indicator plants in locating seleniferous areas in Western United States. I. General. *Amer. J. Bot.*, 26, 257-269.
BEAUCHAMP, C. E. 1939. The composition of the alcohol extract of sugar cane leaves as a means of determining the fertility of the soil for this crop. *Proc. Asoc. Techn. Azuc. Cuba;* 13, 273-284.
——— 1940. The mineral composition of the alcoholic extract of potato leaves and its relationship to crop yields. *Plant Physiol.*, 15, 485-502.
——— 1940a. The mineral composition of the entire leaves of sugar cane and of the alcoholic extract of the leaves as indicators of soil fertility. *Proc. Asoc. Techn. Azuc. Cuba*, 14.
——— 1942. Composition of alcoholic leaf extract and the entire leaf of Irish potatoes as indices of soil fertility. *Plant Physiol.*, 17, 165-178.
——— and ALVARINO, J. E. 1940. The mineral composition of the leaves of different sugar cane varieties and its possible relationship with the efficiency of their mineral nutrition. *Proc. Asoc. Techn. Azuc. Cuba*, 14, 45-55.
——— and LAZO, F. 1938. The composition of the alcoholic extract of cane leaves and its relationship with cane growth. *Proc. Asoc. Techn. Azuc. Cuba*, 12, 34-47.
——— ——— and BONAZZI, A. 1934. Studies in sugar cane physiology.—V. The content of nitrogen, phosphorus and potash in crude chlorophyll and in the leaf skeleton and its relationship with fertilizers. *Proc. Asoc. Techn. Azuc. Cuba*, 8, 82-114.
——— ——— ——— 1935. Studies on the physiology of sugar cane: VI. The content of nitrogen, phosphorus and potash in fertilizers and their relationship with the composition of the chlorophyll of the leaves and the growth of the cane. *Proc. Asoc. Techn. Azuc. Cuba*, 9, 26-37.
BEAUMONT, A. B., and SNELL, M. E. 1935. The effect of magnesium deficiency on crop plants. *J. agric. Res.*, 50, 553-562.
BECK, A. B. 1941. A survey of the copper content of Western Australian pastures. *J. Dep. Agric. W. Aust.*, 18, 285-300.
BECKER, J. 1940. (The magnesia problem in forest culture.) *Forstarchiv.*, 16, 88-92. [Quoted in *Chem. Abs.*, 34, 5233.]
BEESON, K. C., and SMITH, S. E. 1944. Some areas in the United States associated with deficiencies of cobalt and other elements in the soil. *J. Amer. Soc. Agron.*, 36, 1019.
BEHRENS, W. U. 1935. Die Methoden zur Bestimmung des Kali- und Phosphorsäurebedarfs landwirtschaftlich genutzter Böden. Verlag Chemie, Berlin, pp. 196.
——— 1937. Die Fortschritte in der Bestimmung des Kali- und Phosphorsäurebedarfs der Böden. *Forschungsdienst*, 4, 463-477.
BENECKE, W., and SÖDING, H. 1927. Beiträge zum Ausbau der mikrobiologischen Bodenanalyse. *Z. PflErnähr Düng., A.*, 10, 129-159.
BENNETT, J. P. 1945. Iron in leaves. *Soil Sci.*, 60, 91-105.
BERGER, K. C., and TRUOG, E. 1939. Boron deficiencies as revealed by plant and soil tests. *Amer. Fertil.*, 91 (6), 9.
——— ——— 1939a. Boron determination in soils and plants, using the quinalizarin reaction. *Industr. Engng Chem., Anal. Ed.*, 11, 540-545.
——— ——— 1940. Boron deficiencies as revealed by plant and soil tests. *J. Amer. Soc. Agron.*, 32, 297-301.
——— ——— 1944. Boron tests and determination for soils and plants. *Soil Sci.*, 57, 25-36.
BINNIE, R. R. 1943. Boron improves canning beets. *Better Crops with Plant Food.* 27 (1), 19-22, 49-51.
BLASER, R. E., and STOKES, W. E. 1943. Effect of fertilizer on growth and composition of carpet and other grasses. *Bull. Fla Agric. Exp. Sta.*, 390, 1-31.
BOLAS, B. D., and GOODALL, D. W. 1937. Some aspects of translocation in the tomato plant. Unpublished paper read to Society for Experimental Biology at Oxford, March, 1937.
BORDEN, R. J. 1936. Cane growth studies. The dominating effect of climate. *Hawaii. Plant Rec.*, 40, 143-156.
——— 1936a. Some interesting cane-tonnage, purity, soil-analyses, juice-analyses relationships. *Hawaii. Plant. Rec.*, 40, 11-19.

———— 1936b. Diagnosing the status of available phosphoric acid and potash in sugar cane soils. *Hawaii. Plant. Rec.*, 40, 3-10.
———— 1942. A search for guidance in the nitrogen fertilization of the sugar cane crop. Part I.—The plant crop. *Hawaii. Plant Rec.*, 46, 191-238.
———— 1944. A search for guidance in the nitrogen fertilization of the sugar cane crop. Part II—The first ratoon crop. *Hawaii. Plant Rec.*, 48, 271-306.
BORESCH, K. 1938. Über die Blattrandkrankheit der Johannisbeere mit einem Ausblick auf die Entstehung von Mangelchlorosen. *Gartenbauwiss.*, 12, 176-233.
BORTNER, C. E. 1935. Toxicity of manganese to Turkish tobacco in acid Kentucky soils. *Soil Sci.*, 39, 15-33.
BOWER, C. A., and PIERRE, W. H. 1944. Potassium response of various crops on a high-lime soil in relation to their contents of potassium, calcium, magnesium, and sodium. *J. Amer. Soc. Agron.*, 36, 608-614.
BOYNTON, D. 1942. Progress toward a more scientific basis for orchard fertilization. *Proc. N.Y. St. hort. Soc.*, 87, 192-198.
———— 1944. Responses of young Elberta peach and Montmorency cherry trees to potassium fertilization in New York. *Proc. Amer. Soc. hort. Sci.*, 44, 31-33.
———— 1945. Recent advances in orchard fertilization practices. *Proc. N.Y. St. hort. Soc.*, 90, 67-71.
———— 1945a. Studies on control of magnesium deficiency in New York apple orchards. *Proc. Amer. Soc. hort. Sci.*, 46, 1-5.
———— 1945b. Potassium deficiency in a New York grape vineyard. *Proc. Amer. Soc. hort. Sci.*, 46, 246-248.
———— and BURRELL, A. B. 1944. Effects of nitrogen fertilizer on leaf nitrogen, fruit colour and yield in two New York McIntosh apple orchards, 1942 and 1943. *Proc. Amer. Soc. hort. Sci.*, 44, 25-30.
———— ———— 1944a. Potassium-induced magnesium deficiency in the McIntosh apple tree. *Soil Sci.*, 58, 441-454.
———— and CAIN, J. C. 1942. A survey of the relationships between leaf nitrogen, fruit color, leaf color, and per cent of full crop in some New York McIntosh apple orchards. *Proc. Amer. Soc. hort. Sci.*, 40, 19-22.
———— ———— and COMPTON, O. C. 1944. Soil and seasonal influences on the chemical composition of McIntosh apple leaves in New York. *Proc. Amer. Soc. hort. Sci.*, 44, 15-24.
———— ———— and VAN GELUWE, J. 1943. Incipient magnesium deficiency in some New York orchards. *Proc. Amer. Soc. hort. Sci.*, 42, 95-100.
———— and COMPTON, O. C. 1944. The influence of differential fertilization with ammonium sulfate on the chemical composition of McIntosh apple leaves. *Proc. Amer. Soc. hort. Sci.*, 45, 9-17.
———— ———— 1945. Leaf analysis in estimating the potassium, magnesium, and nitrogen needs of fruit trees. *Soil Sci.*, 59, 339-351.
———— and PEECH, M. 1945. Rapid determination of potassium and magnesium content of apple leaves. *J. Amer. Soc. Agron.*, 37, 404-407.
————, REUTHER, W., and CAIN, J. C. 1941. Leaf analysis and apparent response to potassium in some plum and apple orchards, preliminary report. *Proc. Amer. Soc. hort. Sci.*, 38, 17-20.
BRANDENBURG, E. 1932. Die Herz- und Trockenfäule der Rüben—Ursache und Bekämpfung. *Angew. Bot.*, 14, 194-228.
———— 1932a. Physiologische ziekten der bieten II. Hartrot—oorzaak en bestrijding. *Meded. Inst. Suikerbiet., Bergen-o.-Z.*, 2, 43-75.
———— 1939. Ueber die Grundlagen der Boranwendung in der Landwirtschaft. *Phytopath. Z.*, 12, 1-112.
BRAY, R. H. 1945. Nitrates tests for soils and plant tissues. *Soil Sci.*, 60, 219-221.
BRICKLEY, W. D. 1943. Diseased conditions in potatoes and peas associated with potash deficiency in South County Kildare. *J. Dep. Agric. Éire*, 40, 149-161.

BROWN, B. A. 1940. Boron deficiencies in Connecticut. *Science* (N.S.) 91, 338.
BROWN, D. S. 1945. The growth and composition of the tops of peach trees in sand culture in relation to nutrient-element balance. *Abstr. Doct. Diss., Ohio Univ.*, 46, 19-28.
BROWN, R. J. 1943. Sampling sugar beet petioles for measurement of soil fertility. *Soil Sci.*, 56, 213-222.
BRYAN, O. C. 1929. The stimulating effect of external applications of copper and manganese on certain chlorotic plants of the Florida Everglades soils. *J. Amer. Soc. Agron.*, 21, 923-933.
BURKHART, L. 1941. Foliar diagnosis and plant nutrition. *Proc. Assoc. south. agric. Workers*, 42, 207-208.
——— 1942. Soil and leaf diagnosis in relation to crop nutrition experiments. Amer. Soc. Plant Physiol. Ann. Mtg. 19, 3. [quoted in *Herb. Abs.* 17, 52].
——— and COLLINS, E. R. 1942. Mineral nutrients in peanut plant growth. *Proc. Soil Sci. Soc. Amer.*, 6, 272-280.
——— and PAGE, N. R. 1941. Mineral nutrient extraction and distribution in the peanut plant. *J. Amer. Soc. Agron.*, 33, 743-755.
BURRELL, A. B., and BOYNTON, D. 1943. Response of apple trees to potash in the Champlain Valley III. *Proc. Amer. Soc. hort. Sci.*, 42, 61-64.
——— and CAIN, J. C. 1941. A response of apple trees to potash in the Champlain Valley of New York. *Proc. Amer. Soc. hort. Sci.*, 38, 1-7.
——— ——— and BRINKERHOFF, L. A. 1942. Response of apple trees to potash in the Champlain Valley, II. A third-year growth response and a first-year reduction in leaf scorch. *Proc. Amer. Soc. hort. Sci.*, 40, 8-12.
BURSTRÖM, H. 1934. Über antagonistische Erscheinungen bei der Kationenaufnahme des Hafers. *Svensk bot. Tidskr.*, 28, 157-263.
——— 1937. Kemisk-fysiologisk analys av kalknings- och gödslingsförsök på sur lerjord. [German summary.] *K. LandbrAkad. Handl., Stockh.*, 76, 304-353. *Medd. CentAnst. Försöksv. Jordbr., Stockh.*, 475.
BUSLOVA, E. D. 1939. On the diagnosis of mineral starvation of chlorotic plants. [Russian, with English summary.] *Zhur. Inst. Bot. Akad. Nauk. U.R.S.R.*, 23 (31), 145-159. [quoted in *Herb. Abs.*, 11, 32, 1941].
BUTKEVIČ, W. 1909. The culture of the fungus *Aspergillus niger* as a method of soil investigation. [Russian, with German summary.] *Russ. J. exp. Agric.*, 10, 136-141.
BYERS, H. G., MILLER, J. T., WILLIAMS, K. T., and LAKIN, H. W. 1938. Selenium occurrence in certain soils in the United States with a discussion of related topics: third report. *Tech. Bull. U.S. Dep. Agric.*, 601, 1-74.
CAPÓ, B. G. 1938. A modification of Mitscherlich's method for the determination of the nutrient contents of a soil. *J. Dep. Agric. P.R.*, 22, 137-169.
CAROLUS, R. L. 1933. Some significant variations in the chemical composition of the plant associated with a malnutrition trouble of potatoes. *Amer. Potato J.*, 10, 147-165.
——— 1933a. Tomato fertilization, II. The effect of different fertilizer ratios on the chemical composition of tomatoes. *Bull. Va Truck Exp. Sta.*, 81, 1085-1117.
——— 1934. Some factors affecting the absorption of magnesium by the potato plant. *Proc. Amer. Soc. hort. Sci.*, 30, 480-484.
——— 1935. Effects of magnesium deficiency in the soil on the yield, appearance and composition of vegetable crops. *Proc. Amer. Soc. hort. Sci.*, 32, 610-614.
———, 1936. Experiences with rapid chemical tests for the determination of nutrient deficiencies in vegetable crops. *Proc. Amer. Soc. hort. Sci.*, 33, 579-583.
———, 1937. Chemical estimations of the weekly nutrient level of a potato crop. *Amer. Potato J.*, 14, 141-153.
———, 1938. The use of rapid chemical plant nutrient tests in fertilizer deficiency diagnoses and vegetable crop research. *Bull. Va Truck Exp. Sta.*, 98, 1531-1556.
———, 1938a. Effect of certain ions, used singly and in combination, on the growth and potassium, calcium, and magnesium absorption of the bean plant. *Plant Physiol.*, 13, 348-363.
———, and BROWN, B. E. 1935. Magnesium deficiency I. The value of magnesium com-

pounds in vegetable production in Virginia. *Bull. Va Truck Exp. Sta.*, 89, 1250-1288.
————, Hester, J. B., and Blume, J. M. 1938. The reliability of rapid chemical plant tests as a means of diagnosing fertilizer deficiencies in vegetable crops. *Amer. Fertil.*, 89 (1), 7-8, 24.
Carson, R. B., Tottingham, W. E., and MacVicar, R. 1941. The comparative boron content of potato leaves and tubers produced under different cultural conditions. *Amer. Fertil.*, 94 (7), 8.
Cawthron Institute. 1942. Fruit research. *Rep. Cawthron Inst. for* 1941, 15-20.
———————— 1943. Fruit research. (1) Leaf tests for mineral deficiencies. *Rep. Cawthron Inst for* 1942, 13-14.
Chaminade, R. 1942. Observations sûr la composition minérale du tubercule de pomme de terre. *Ann. agron.* (*N.S.*), 12, 45-58.
Chandler, R. F., Jr. 1936. Absorption, distribution, and seasonal movement of potassium in young trees and the effect of potassium fertiliser on potassium and nitrogen content and growth of trees. *J. agric. Res.*, 53, 19-42.
Chandler, W. H., Hoagland, D. R., and Hibbard, P. L. 1934. Little-leaf or rosette of fruit trees, III. *Proc. Amer. Soc. hort. Sci.*, 30, 70-86.
Chapman, G. W. 1931. The relation of iron and manganese to chlorosis in plants. *New Phytol.*, 30, 266-283.
———— 1941. Leaf analysis and plant nutrition. *Soil Sci.*, 52, 63-81.
Chapman, H. D. 1935. Inorganic phosphate in green plant tissue as a measure of phosphate availability. *Soil Sci.*, 39, 111-122.
———— and Brown, S. M. 1941. The effects of phosphorus deficiency on citrus. *Hilgardia*, 14, 161-181.
———— ———— 1941a. The effects of sulfur deficiency on citrus. *Hilgardia*, 14, 185-201.
———— ———— 1942. Potash in relation to citrus nutrition. *Canning Age*, 23, 581-582.
———— ———— 1943. Potash in relation to citrus nutrition. *Soil Sci.*, 55, 87-100.
———— ———— 1943a. Leaf analysis reveals needs. New method for estimating the fertilizer needs of citrus trees. California experiments. *Citrus Leaves*, 23 (11), 9.
———— ———— and Rayner, D. S. 1944. Diagnosing the fertility needs of citrus trees. *Calif. Citrogr.*, 29, 182.
————, and Liebig, G. F., Jr. 1940. Nitrate concentration and ion balance in relation to citrus nutrition. *Hilgardia*, 13, 141-173.
———— ———— and Parker, E. R. 1939. Manganese studies on Calif. soils and citrus leaf symptoms of deficiency. *Calif. Citrogr.*, 24, 427, 454 ; 25, 11, 15.
———— ———— and Vanselow, A. P. 1940. Some nutritional relationships as revealed by a study of mineral deficiency and excess symptoms on citrus. *Proc. Soil. Sci. Soc. Amer.*, 4, 196-200.
Chemistry Department, Experiment Station, Hawaiian Sugar Planters' Association. 1944. Soil and plant material analyses by rapid chemical methods IV. The Clements' method of crop control adapted to RCM. *Hawaii. Plant. Rec.*, 48, 213-230.
Chibnall, A. C. 1922. Investigations on the nitrogenous metabolism of the higher plants. Part II. The distribution of nitrogen in the leaves of the runner bean. *Biochem. J.*, 16, 344-362.
Chilean Nitrate Education Bureau, Inc. 1941. If they could speak. New York, pp. 54.
Chittenden, E., and Thomson, R. H. K. 1938. The effect of borax top-dressing on the storage quality of Jonathan apples. *N. Z. J. Sci. Tech.*, 19, 541-546.
Christensen, H. R. 1906. Om nyere Principper i Jordbundsforskningen. Samt nogle Meddelelser om *Azotobacter chroococcum's* Forekomst og Udbredelse i forskellige Jorder. *Tidsskr. Landbr. Planteavl*, 13, 145-194.
———— 1914. Studier over Jordbundsbeskaffenhedens Indflydelse paa Bakterielivet og Stofomsaetningen i Jordbunden. *Tidsskr. Planteavl.*, 21, 321-552.
———— 1922. Untersuchungen über das Kalkbedürfnis des Bodens. *Z. PflErnähr. Düng. A.*, 1, 265-290.
————, and Larsen, O. H. 1910. Undersøgelser over Jordens Kalktrang. *Tidsskr. Landbr. Planteavl*, 17, 407-509.

CLARK, H. E. and POWERS, W. L. 1945. Leaf analysis as an indicator of potassium requirement of cane fruits. *Plant Physiol.*, 20, 51-61.
CLARKE, E. J. 1944. Studies on tomato nutrition—I. The effect of varying concentrations of potassium on the growth and yields of tomato plants. *J. Dep. Agric. Éire*, 41, 53-81.
CLEMENTS, H. F. 1940. Integration of climatic and physiologic factors with reference to the production of sugar cane. *Hawaii. Plant. Rec.*, 44, 201-233.
———, AKAMINE, —, SHIGEURA,—and MORIGUCHI, —. 1945. Plant physiology. The crop-log for use in sugarcane production. *Rep. Hawaii. agric., Exp. Sta. for* 1942-4, 34-40.
———, and KUBOTA, T. 1942. Internal moisture relations of sugar cane.—The selection of a moisture index. *Hawaii. Plant. Rec.*, 46, 17-36.
——— ——— 1943. The primary index, its meaning and application to crop management with special reference to sugar cane. *Hawaii. Plant .Rec.*, 47, 257-297.
———, MARTIN, J. F. and MORIGUCHI, S. 1941. Composition of sugar cane plants grown in deficient nutrient solutions. *Hawaii. Plant. Rec.*, 45, 227-239.
——— and MORIGUCHI, S. 1942. Nitrogen and sugar cane. The nitrogen index and certain quantitative field aspects. *Hawaii. Plant. Rec.*, 46, 163-190.
COLLINS, E. R. 1942. Comparison of soil tests, tissue analysis and seed analysis as an index of soil fertility with peanuts. *Proc. Assoc. south. agric. Workers*, 43, 78-79.
———, BURKHART, L. and MORRIS, H. D. 1941. Correlation of soil and tissue tests as an index of nutrient levels for peanut production. *Proc. Assoc. south. agric. Workers*, 42, 54-55.
——— and MORRIS, H. D. 1942. Soil fertility studies with peanuts. *Bull. N. C. agric. Exp. Sta.* 330, 1-23.
COLWELL, W. E. 1943. A biological method for determining the relative boron contents of soils. *Soil. Sci.*, 56, 71-94.
——— and BAKER, G. O. 1939. Studies of boron deficiency in Idaho soils. *J. Amer. Soc. Agron.*, 31, 503-512.
COMPTON, O. C., and BOYNTON, D. 1945. A rapid method for the determination of chlorophyll in apple leaves. *Proc. Amer. Soc. hort. Sci.*, 46, 45-50.
COOK, H. L. 1941. Plant tissue tests in studying effectiveness of fertilizer placement. *Proc. nat. Jt. Comm. Fert. Appl.*, 17, 38.
——— 1941a. Correlation of plant tissue tests with fertilizer treatments and yields of corn. *Proc. nat. Jt. Comm. Fert. Appl.*, 17, 37.
COOK, R. L. 1930. Effect of soil type and fertilizer on the nitrate content of the expressed sap and the total nitrogen content of the tissue of the small grains. *J. Amer. Soc. Agron.*, 22, 393-408.
——— 1941. Plant symptoms show need for potash. *Better Crops with Plant Food*, 25 (10), 17-20, 36-39.
——— and MILLAR, C. E. 1940. Some soil factors affecting boron availability. *Proc. Soil Sci. Soc. Amer.*, 4, 297-301.
COOPER, H. P., and GARMAN, W. H. 1943. Effect of applications of sodium on the composition and yield of cotton at different levels of potash fertilization. *Proc. Soil Sci. Soc. Amer.*, 7, 331-338.
COOPER, T. P. 1937. Boron in plant growth. *Rep. Ky agric. Exp. Sta.*, 49, 21-22.
CRAIG, N. 1934. Part II. Biochemistry. Manurial trials. *Rep. Sug. Cane Res. Sta. Mauritius*, 4, 29-33.
——— 1934a. Contribution de la Station de Recherches du Département d'Agriculture. Résultats d'une experience culturale avec de l'engrais phosphaté, faite à l'établissement St. Aubin. *Rev. agric. Maurice*, No. 73, 10-11.
——— 1943b. Études sur l'assimilabilité des phosphates dans les sols de Maurice. *Rev. agric. Maurice*, No. 74, 41-45.
——— 1938. Part II.—Chemistry. *Rep. Sug. Cane Res. Sta. Mauritius*, 8, 33-46.
——— 1939. Part II.—Chemistry. Foliar diagnosis. *Rep. Sug. Cane Res. Sta. Mauritius*, 9, 30-37.
——— 1939a. Part II.—Chemistry. Juice analysis of sugar cane. *Rep. Sug. Cane Res. Sta. Mauritius*, 9, 37-38.

———— 1940. Part II.—Chemistry. *Rep. Sug. Cane Res. Sta. Mauritius*, 10, 17-29.
———— 1941. Part II.—Chemistry. *Rep. Sug. Cane Res. Sta. Mauritius*, 11, 11-17.
———— 1942. Part II.—Chemistry. *Rep. Sug. Cane Res. Sta. Mauritius*, 12, 14-21.
———— and HALAIS, P. 1941. Le diagnostic foliaire. Méthode de controle biochimique de l'alimentation minérale des cultures de canne à sucre. *Rev. agric. Maurice*, 23, 120-132.
CROMWELL, B. T., and HUNTER, J. G. 1942. Chlorosis in tomatoes. *Nature, Lond.*, 150, 606-607.
CROWTHER, F. 1936. Experiments in Egypt on the interaction of factors in crop growth. 3. The effects of variety, spacing, nitrogen and water supply on the development of the cotton plant and the rate of its absorption of nitrogenous fertilizer. *Bull. Tech. Sect. Soc. Agric. Caire* 25, 1-49.
———— 1937. Experiments in Egypt on the interaction of factors in crop growth. 7. The influence of manuring on the development of the cotton crop. *Bull. tech. Sect. Soc. Agric. Caire* 31, 1-70.
———— 1941. Studies in growth analysis of the cotton plant under irrigation in the Sudan. II. Seasonal variation in development and yield. *Ann. Bot., Lond.* (*N.S.*), 5, 509-533.
CULLINAN, F. P., and BATJER, L. P. 1942. Nitrogen, phosphorus, and potassium interrelationships in young peach and apple trees. *Amer. Fertil.*, 97 (6), 20.
———— ———— 1943. Nitrogen, phosphorus, and potassium interrelationships in young peach and apple trees. *Soil Sci.*, 55, 49-60.
————, SCOTT, D. H., and WAUGH, J. G. 1939. The effects of varying amounts of nitrogen, potassium and phosphorus on the growth of young peach trees. *Proc. Amer. Soc. hort. Sci.*, 36, 61-68.
———— and WAUGH, J. G. 1940. Response of peach trees to potassium under field conditions. *Proc. Amer. Soc. hort. Sci.*, 37, 87-94.
DANIEL, H. A., and HARPER, H. J. 1934. The relation between total calcium and phosphorus in mature prairie grass and available plant food in the soil. *J. Amer. Soc. Agron.*, 26, 986-992.
DARROW, G. M., and MAGNESS, J. R., 1939. Investigations on mulching red raspberries. *Proc. Amer. Soc. hort. Sci.*, 36, 481-484.
DAS, U. K. 1936. Nitrogen nutrition of sugar-cane. *Plant Physiol.*, 11, 251-317.
DAVIDSON, O. W., and BLAKE, M. A. 1938. Nutrient deficiency and nutrient balance with the peach. *Proc. Amer. Soc. hort. Sci.*, 35, 339-346.
DAVIES, R. O., FAGAN, T. W., and JOHN, J. L. 1944. Requirements of the potato on acidic bracken land. *Emp. J. exp. Agric.*, 12, 54-60.
DAVIES, W. M. 1940. Analysis as a guide to soil treatment. The composition of soils and crops. *J. R. agric. Soc.*, 100 (3), 20-34.
DEAN, L. A., and TANADA, T. 1943. Soil and plant investigations. Micronutrient investigations. *Rep. Hawaii. agric. Exp. Sta. for* 1941, 56-57.
DICKEY, R. D., and DROSDOFF, M. 1943. Control of manganese deficiency in a commercial tung orchard. *Proc. Amer. Soc. hort. Sci.*, 42, 74-78.
VON DIKOW, A. 1891. Beurtheilung des Bodens nach den Wurzeln der Gerstenpflanze. *J. Landw.*, 39, 134-147.
DIRKS, B., and SCHEFFER, F. 1928. Vergleichende Untersuchungen über das Nährstoffbedürfnis der Kulturböden. *Landw. Jb.*, 67, 779-821.
DOI, M. 1944. Leaf-punch nitrogen studies on first ratoon crop of 32-8560 at Waipio. *Hawaii. Plant. Rec.*, 48, 237-247.
DRAKE, M. 1941. The plant tissue test may be used to study effectiveness of side-dress applications of fertilizer. *Proc. nat. Jt. Comm. Fert. Appl.*, 17, 42.
———— 1944. Nutrient balance in corn growing in Southern States as revealed by Purdue plant tissue tests. *J. Amer. Soc. Agron.*, 36, 1-9.
———— and SCARSETH, G. D. 1940. Relative abilities of different plants to absorb potassium and the effects of different levels of potassium on the absorption of calcium and magnesium. *Proc. Soil Sci. Soc. Amer.*, 4, 201-204.

DRAKE, M., SIELING, D. H., and SCARSETH, G. D. 1941. Calcium-boron ratio as an important factor in controlling the boron starvation of plants. *J. Amer. Soc. Agron.*, 33, 454-462.
DREGNE, H. E., and POWERS, W. L. 1942. Boron fertilization of alfalfa and other legumes in Oregon. *J. Amer. Soc. Agron.*, 34, 902-912.
DROSDOFF, M. 1943. Fertilizing tung trees by leaf analysis. *Better Crops with Plant Food*, 27 (4), 9-13, 49-50.
———— 1944. Leaf composition in relation to the mineral nutrition of tung trees. *Soil. Sci.*, 57, 281-291.
———— and DICKEY, R. D. 1943. Copper deficiency of tung trees. *Proc. Amer. Soc. hort. Sci.*, 42, 79-84.
———— and KENWORTHY, A. L. 1944. Magnesium deficiency of tung trees. *Proc. Amer. Soc. hort. Sci.*, 44, 1-7.
———— and PAINTER, J. H. 1942. A chlorosis and necrosis of tung leaves associated with low potassium content. *Proc. Amer. Soc. hort. Sci.*, 41, 45-51.
DUGGAN, J. B. 1943. A promising attempt to cure chlorosis, due to manganese deficiency, in a commercial cherry orchard. *J. Pomol.*, 20, 69-79.
DUNBAR, C. O., and ANTHONY, R. D. 1938. Two cases of potassium deficiency in peach orchards in South Central Pennsylvania. *Proc. Amer. Soc. hort. Sci.*, 35, 320-325.
DUNNE, T. C. 1938. "Wither tip" or "summer dieback". A copper deficiency disease of apple trees. *J. Dep. Agric. W. Aust.*, 15, 120-126.
EATON, F. M. 1932. Boron requirements of cotton. *Soil Sci.*, 34, 301-305.
———— 1935. Boron in soils and irrigation waters and its effect on plants with particular reference to the San Joaquin Valley of California. *Tech. Bull. U.S. Dep. Agric.*, 448, 1-131.
———— 1944. Deficiency, toxicity, and accumulation of boron in plants. *J. agric. Res.*, 69, 237-277.
———— and BLAIR, G. Y. 1935. Accumulation of boron by reciprocally grafted plants. *Plant Physiol.*, 10, 411-424.
————, MCCALLUM, R. D., and MAYHUGH, M. S. 1941. Quality of irrigation waters of the Hollister area of California with special reference to boron content and its effect on apricots and prunes. *Tech. Bull. U.S. Dep. Agric.*, 746, 1-59.
EATON, S. V. 1935. Influence of sulphur deficiency on the metabolism of the soy bean. *Bot. Gaz.*, 97, 68-100.
———— 1941. Influence of sulphur deficiency on metabolism of the sunflower. *Bot. Gaz.*, 102, 536-556.
———— 1942. Influence of sulphur deficiency on metabolism of black mustard. *Bot. Gaz.*, 104, 306-315.
ECKSTEIN, O., and JACOB, A. 1929. Der Kali-Eisen Antagonismus in der Pflanze als Grundlage einer Methode zur Feststellung des Kalibedürfnisses der Böden. *Z, PflErnähr. Düng. A.*, 14, 205-220.
———— ———— and ALTEN, F. 1931. Arbeiten über Kalidüngung. Verlagsgesellschaft für Ackerbau, Berlin, pp. 237.
EDGERTON, —. 1941. Thesis, Cornell University. [quoted by Drosdoff, 1944].
EDLER, —. 1898. Versuche zur Ermittelung des Düngerbedürfnisses des Ackerbodens. A. Die Felddüngungsversuche 1895. *J. Landw.*, 46, 349-365.
EHRENBURG, P. 1919. Das Kalk-Kali-Gesetz. Neue Ratschläge zur Vermeidung von Misserfolgen bei der Kalidüngung. Gleichzeitig ein Versuch zur Aufklärung der nachteilige Wirkung grösserer Kalkgaben auf das Pflanzenwachstum. *Landw. Jb.*, 54, 1-154.
EICHINGER, —. 1929. Beziehung von Unkrautflora und Kalkzustand des Bodens zum möglichen Anbau von Kulturpflanzen und zur Wirkung der Düngemittel. *Mitt. dtsch. LandwGes.*, 44, 407-410.
EMMERLING, —. 1875. *Landw. Wochenbl. Schles. Holst.*, 265-267, 271-273. Quoted by Helmkampf, 1892.
EMMERT, E. M. 1929. The determination of nitrate in green tomato and lettuce tissues. *Plant Physiol.*, 4, 519-528.

———— 1929a. The chlorate method for the determination of nitrate nitrogen, total nitrogen, and other elements in soils and plant tissues. *J. Ass. off. agric. Chem., Wash.*, 12, 240-247.
———— 1930. A method for the rapid determination of phosphate in fresh plant tissues. *Plant Physiol.*, 5, 413-416.
———— 1931. The effect of soil reaction on the growth of tomatoes and lettuce and on the nitrogen, phosphorus and manganese content of the soil and plant. *Bull. Ky agric. Exp. Sta.* 314, 1-83.
———— 1932. Field method for estimating nitrate, phosphate, and potassium in plants. *Plant Physiol.*, 7, 315-321.
———— 1934. Tests for phosphate, nitrate and soluble nitrogen in conducting tissue of tomato and lettuce plants, as indicators of availability and yield. *Circ. Ky agric. Exp. Sta.* 43, 26-40.
———— 1935. Tests for nutrients in conducting tissue as indicators of the nutritional status in horticultural crops. *Proc. Amer. Soc. hort. Sci.*, 32, 604-609.
———— 1935a. New methods for the determination of the availability of nitrogen and phosphorus to plants. *J. Amer. Soc. Agron.*, 27, 1-7.
———— 1935b. Method for quickly determining nitrogen in plants, and soluble nitrogen as a measure of the nitrogen available for anabolic processes. *Plant Physiol.*, 10, 355-364.
———— 1936. The correlation of soluble nitrogen and phosphate phosphorus in the conducting tissues of potatoes at various stages of growth with yield. *Proc. Amer. Soc. hort. Sci.*, 33, 589-594.
———— 1937. The use of partial linear regression to analyze the curvilinear relationship between the yield of vegetable crops and the content of nutrients in the lower main stems. *J. Amer. Soc. Agron.*, 29, 213-219.
———— 1941. Plant tests as a guide to fertilizer treatment of tomatoes (Preliminary report). *Proc. Amer. Soc. hort. Sci.*, 38, 621-622.
———— 1942. The importance of determining the concentration of carbon in plant extracts in diagnosing mineral deficiencies by plant tissue tests. *Proc. Assoc. south. agric. Workers*, 43, 209.
———— 1942a. Plant-tissue tests as a guide to fertilizer treatment of tomatoes. *Bull. Ky agric. Exp. Sta.* 430, 1-48.
———— 1944. Use of monochloracetic acid to include ammonia in the "soluble nitrogen" tissue test. *Plant Physiol.*, 19, 562-563.
———— 1944a. Modification of the phenoldisulfonic acid method for potassium to increase rapidity and accuracy. *Proc. Amer. Soc. hort. Sci.*, 45, 311-312.
Empire Cotton Growing Corporation. 1942. Report of the administrative council of the corporation submitted to the twenty-first Annual General Meeting on June 2nd, 1942. Annual report for the season 1940-1941, 1-18.
———— 1943. Report of the administrative council of the corporation submitted to the twenty-second Annual General Meeting on June 1st, 1943. Annual report for the season 1941-1942, 1-16.
Epstein, E., and Lilleland, O. 1942. A preliminary study of the manganese content of the leaves of some deciduous fruit trees. *Proc. Amer. Soc. hort. Sci.*, 41, 11-18.
Evans, H. 1940. Part III—Research Botany. *Rep. Sug. Cane Res. Sta. Mauritius*, 10, 30-46.
———— 1941. Part III.—Research Botany. *Rep. Sug. Cane Res. Sta. Mauritius*, 11, 17-29.
———— 1942. An investigation of physiological methods of determining nutrient deficiencies in sugar-cane. *Ann. Bot., Lond.* (*N.S.*), 6, 413-436.
von Feilitzen, H. 1910. Werden die Moorwiesen genügend gedüngt? *Mitt. Ver. Moork., Berl.*, 28, 265-268.
———— 1910a. Werden die Moorwiesen genügend gedüngt? *Mitt. Ver. Moork., Berl.*, 28, 341-344.
Ferguson, W., and Wright, L. E. 1940. Micro-element studies with special reference to the element boron. *Sci. Agric.*, 20, 470-487.

FERRES, H. M., and TRUMBLE, H. C. 1943. Exploratory investigations of soil deficiencies by means of small pot cultures. *J. Aust. Inst. agric. Sci.* 9, 179-182.
FINCH, A. H. 1933. Pecan rosette, a physiological disease apparently susceptible to treatment with zinc. *Proc. Amer. Soc. hort Sci.*, 29, 264-266.
———— 1936. Zinc and other mineral constituents in relation to the rosette disease of pecan trees. *J. agric. Res.*, 52, 363-376.
———— 1944. Fertilizing desert grapefruit. *Calif. Citrogr.*, 30, 34-35.
———— and KINNISON, A. F. 1933. Pecan rosette : soil, chemical, and physiological studies. *Tech. Bull. Ariz. agric. Exp. Sta.* 47, 407-442.
FINN, R. F. 1942. Notes on the resampling of certain fertilized plots. *Black Rock For. Pap.*, 1, 104-105.
———— 1942a. Mycorrhizal inoculation of soil of low fertility. *Black Rock For. Pap.*, 1, 116-117.
———— and TRYON, H. H. 1942. The comparative influence of leaf mould and inorganic fertilizers on the growth of red oak. *Black Rock For. Pap.*, 1, 108-109.
FITZPATRICK, R. E., and WOODBRIDGE, C. G. 1941. Boron deficiency in apricots. *Sci. Agric.*, 22, 271-273.
FOLLETT-SMITH, R. R. 1934. Report of the chemical division for the year 1933. Sugar cane soil investigations. Soil salinity and magnesium toxicity. *Div. Rep. Dep. Agric. Brit. Guiana for* 1933, 90-92.
———— 1939. A note on the sugarcane soils of British Guiana. *Proc. int. Soc. Sug. Cane Tech.*, 6, 326-333.
FONDER, J. F. 1929. The relationship of soil type to the calcium and magnesium content of green bean stems and leaves and of their expressed juice. *Soil Sci.*, 27, 415-431.
———— 1929a. A critical study of the influence of soil type on the calcium and magnesium content and other physiological characters of the alfalfa plant. *Soil Sci.*, 27, 205-232.
FRAPS, G. S. 1912. Relation of the total nitrogen of the soil to its needs as shown in pot experiments. *Bull. Tex. agric. Exp. Sta.* 151, 1-15.
———— 1931. How reliable are existing chemical methods for determining soil deficiencies in ash constituents of plants ? *J. Amer. Soc. Agron.*, 23, 337-351.
————, FUDGE, L. F., and REYNOLDS, E. B. 1937. Effect of fertilization on the composition of a Lufkin fine sandy loam and of oats grown on it. *J. Amer. Soc. Agron.*, 29, 990-996.
FREAR, D. E. H., and ANTHONY, R. D. 1943. The influence of date of sampling on the value of leaf weights and chemical analyses in nutrition experiments with apple trees. *Proc. Amer. Soc. hort. Sci.*, 42, 115-122.
FUDGE, B. R. 1938. Magnesium deficiency in relation to yield and chemical composition of seedy and commercially seedless varieties of grapefruit. *Proc. Fla hort. Soc.* 51, 34-43.
———— 1939. Relation of magnesium deficiency in grapefruit leaves to yield and chemical composition of fruit. *Bull. Fla agric. Exp. Sta.* 331, 1-36.
———— 1941. The mineral composition of citrus juice as influenced by soil treatment. *Citrus Ind.*, 22 (10), 3, 6, 7, 14, 15.
———— 1942. Early diagnosis of magnesium deficiency in Florida citrus. *Citrus Ind.*, 23 (9), 1, 4-5, 14. [quoted in *Chem. Abs.*, 37, 3213].
———— 1942a. Early diagnosis of magnesium deficiency in citrus. *Proc. Fla hort. Soc.*, 55, 17-21. [Quoted in *Exp. Sta. Rec.*, 89, 232.]
———— 1942b. Citrus nutrition studies. Physiological studies. *Rep. Fla agric. Exp. Sta. for* 1941-2. 143-145.
———— 1943. Citrus nutrition studies. Physiological studies. *Rep. Fla agric. Exp. Sta. for* 1942-3, 203-207.
GADDUM, L. W., CAMP, A. F., and REUTHER, W. 1937. Spectrographic studies of the composition of tissues and corresponding soils of normal and physiologically diseased horticultural crops. *Rep. Fla agric. Exp. Sta. for* 1935-6, 82-84.
GALLAGHER, P. H., and WALSH, T. 1943. The influence of manganese on the growth of cereals. *Min. Proc. R. Irish Acad. B.*, 49, 187-200.
GARDENERS' CHRONICLE. 1942. Tell-tales of soil deficiencies. *Gdnrs' Chron.*, 112, 244.

GARDINER, J. G. 1940. Science service. Division of chemistry. Plant chemistry. *Rep. Dep. Agric. Canada for* 1939-40, 43-44.
GARDNER, R., and ROBERTSON, D. W. 1935. The use of sugar beet petioles as indicators of soil fertility needs. *Tech. Bull. Colo. agric. Exp. Sta.* 14, 1-16.
GARNER, W. W. 1939. Some aspects of the physiology and nutrition of tobacco. *J. Amer. Soc. Agron.*, 31, 459-471.
————, BACON, C. W., BOWLING, J. D., and BROWN, D. E. 1934. The nitrogen nutrition of tobacco. *Tech. Bull. U.S. Dep. Agric.* 414, 1-77.
————, MCMURTREY, J. E. Jr., BOWLING, J. D. Jr., and MOSS, E. G. 1930. Magnesium and calcium requirements of the tobacco crop. *J. agric. Res.*, 40, 145-168.
GASSNER, G., and GOEZE, G. 1932. Zur Frage der Frosthärtebestimmung durch refraktometrische Untersuchung von Pflanzenpresssäften. *Phytopath. Z.*, 4, 387-413.
———— ———— 1936. Versuche zur Bestimmung des aufnehmbaren Bodenstickstoffs durch Bestimmung des Chlorophyllgehaltes. *Ergebn. AgrikChem.*, 4, 106-122.
GAST, P. R. 1937. Studies on the development of conifers in raw humus. III. The growth of Scots pine (*Pinus sylvestris* L.) seedlings in pot cultures of different soils under varied radiation intensities. *Medd. Skogsförsöksanst. Stockh.*, 29, 587-682.
GAUCH, H. G., and WADLEIGH, C. H. 1945. Effect of high concentrations of sodium, calcium, chloride and sulfate on ionic absorption by bean plants. *Soil Sci.*, 59, 139-153.
GERLACH, —. 1926. Die Bestimmung des Düngerbedürfnisses der Böden. *Landw. Jb.*, 63, 339-368.
GILBERT, B. E. 1926. The adaptation of certain colorimetric methods to the estimation of nitrates, phosphates and potassium in plant solutions. *Plant Physiol.*, 1, 191-199.
———— and HARDIN, L. J. 1927. The current mineral nutrient content of the plant solution as a possible means of chemical control of optimum fertilization. *J. agric. Res.*, 35, 185-192.
————, MCLEAN, F. T., and HARDIN, L. J. 1926. The relation of manganese and iron to a lime-induced chlorosis. *Soil Sci.*, 22, 437-446.
———— ———— and ADAMS, W. L. 1927. The current mineral nutrient content of the plant solution as an index of metabolic limiting conditions. *Plant Physiol.*, 2, 139-151.
———— and PEMBER, F. R. 1935. The use of seedling plants to determine soil nutrient deficiencies. Rep. R. I. agric. Exp. Sta., 47, 80-83.
———— and SMITH, J. B. 1929. Nitrates in soil and plant as indexes of the nitrogen needs of a growing crop. *Soil Sci.*, 27, 459-468.
GILDEHAUS, E. J. 1931. The relation of nitrogen to potassium in the nutrition of fruit trees. *Bot. Gaz.*, 92, 384-395.
GILE, P. L. 1911. Relation of calcareous soils to pineapple chlorosis. *Bull. P.R. [fed.] agric. Exp. Sta.* 11, 1-45.
GILLIGAN, G. M. 1939. Nutrient absorption by sweet potatoes as affected by fertilizer placement on Sassafras sand. *Bull. Del. agric. Exp. Sta.* 220 (*Rep. for* 1939), 21.
VAN GINNEKEN, P. J. H., and BRUINSMA, J. R. 1938. Onderzoek omtrent de minerale samenstelling van loof en wortel van suikerbieten. II. Verkregen cijfers en eenige daaruit afgeleide conclusies omtrent de beteekenis der verschillende elementen voor een goede suikeropbrengst. [French summary.] *Meded. Inst. Suikerbiet. Bergen-o.-Z.*, 8, 227-317.
GLASSCOCK, H. H., and WAIN, R. L. 1940. Distribution of manganese in the pea seed in relation to marsh spot. *J. agric. Sci.*, 30, 132-140.
GLENISTER, P. R. 1944. Effects of iron deficiency on respiration of sunflower plants. *Bot. Gaz.*, 106, 33-40.
GODLEWSKI, E. 1901. Ueber das Nährstoffbedürfnis einiger Culturpflanzen und über die Abhängigkeit der Zusammensetzung der geernteten Pflanzensubstanz von der chemischen Beschaffenheit des Bodens. *Z. landw. VersWes. Öst.*, 4, 479-536.
GOODALL, D. W. 1943. Studies in the diagnosis of mineral deficiency I. The distribution of certain cations in apple foliage in early autumn. *J. Pomol.*, 20, 136-143.
———— 1943a. Studies in the diagnosis of mineral deficiency II. A comparison of the mineral content of scorched and healthy leaves from the same apple tree. *J. Pomol.*, 21, 90-102.

GOODALL, D. W. 1945a. Studies in the diagnosis of mineral deficiency III. The mineral composition of different types of leaf on apple trees in early summer. *J. Pomol.*, 21, 103-107.
———— 1945b. The distribution of weight change in the young tomato plant I. Dry-weight changes of the various organs. *Ann. Bot., Lond.* N.S., 9, 101-139.
———— 1945c. Report on work done in 1944. Agric. Res. Coun. Unpublished report duplicated for private circulation. A.R.C. 7849, 23-24.
GOSSARD, A. C. 1943. A study of methods of sampling pecan leaves for total nitrogen analysis. *Proc. Amer. Soc. hort. Sci.*, 42, 109-114.
GREEN, J. 1943. Phosphorus and nitrogen deficiency symptoms in sugar beets. *Proc. Amer. Soc. Sugar Beet Technol.* 3, 101-102.
GREENHILL, A. W. 1945. Report on plant tissue tests carried out during 1944. Agric. Res. Coun. Unpublished report duplicated for private circulation. A.R.C. 7829, pp. 1-2.
GREGORY, F. G. 1937. Mineral nutrition of plants. *Ann. Rev. Biochem.*, 6, 557-578.
GREISENEGGER, —., and VORBUCHNER, —. 1918. *Öst-ung. Z. Zuckerind. Landw.*, 47, 281. [quoted by Neubauer and Schneider].
GRIBBINS, M. F., REID, J. J., and HALEY, D. E. 1941. The distribution of potassium in bright leaf cigarette tobacco and its influence on the quality of the leaf. *J. agric. Res.*, 63, 31-39.
GRIMMETT, R. E. R. 1938. Mineral deficiencies and fruit tree growth. *Rep. Dep. Agric., N.Z. for* 1937-8, 58.
GRIS, E. 1844. Nouvelles expériences sur l'action des composés ferrugineux solubles appliqués à la végétation, et spécialement au traitement de la chlorose et de la débilité des plantes. *C. R. Acad. Sci. Paris*, 19, 1118-1119.
GUEST, P. L. 1941. Horticulture. Macadamia chlorosis. *Rep. Hawaii. agric. Exp. Sta. for* 1940. 49-50.
———— 1943. A comparison of certain chemical constituents of green and chlorotic Macadamia leaves. *Proc. Amer. Soc. hort. Sci.*, 42, 104-108.
GUM, O. B., BROWN, H. D., and BURRELL, R. C. 1945. Some effects of boron and manganese on the quality of beets and tomatoes. *Plant Physiol.*, 20, 267-275.
DE HAAN, I. 1941. Gebrekverschijnselen bij thee veroorzaakt door een tekort aan de belangrijkste minerale voedingsstoffen med uitzondering van kalium. [English summary.] *Arch. Theecult. Ned.-Ind.*, 15, 1-32.
——— and SCHOOREL, A. F. 1940. Kaligebrek in de theecultuur. [English summary.] *Arch. Theecult. Ned.-Ind.*, 14, 43-81.
DE HAAN, K. 1937. Resultaat der mangaanproefvelden in 1935 en '36. *Meded. Inst. Suikerbiet., Bergen-o-Z.*, 7, 227-235.
HAAS, A. R. C. 1929. Composition of avocado trees in relation to chlorosis and tip-burn. *Bot. Gaz.*, 87, 422-430.
———— 1936. Phosphorus nutrition of citrus and the beneficial effect of aluminium. *Soil Sci.*, 42, 187-201.
———— 1936a. Chlorine in relation to ring-neck in avocado fruits. *Yearb. Calif. Avocado Assoc. for* 1936, 60-62.
———— 1936b. Deficiency chloroses in citrus. *Soil Sci.*, 42, 435-443.
———— 1937. Boron-deficiency effects similar in general appearance to bark symptoms of psorosis in citrus. *Soil Sci.*, 43, 317-325.
———— 1943. Boron content of avocado trees and soils. *Yearb. Calif. Avocado Assoc. for* 1943, 41-52.
———— 1944. Boron in the palms and soils of date gardens in the Coachella Valley of Southern California. *Proc. Amer. Soc. hort. Sci.*, 44, 34-42.
———— 1945. Boron in citrus trees. *Plant Physiol.*, 20, 323-343.
———— 1945. Boron content of citrus trees grown on various rootstocks. *Soil Sci.*, 59, 465-479.
HADDOCK, J. L. 1934. Methods for determining magnesium deficiency in soils. *Bull. Mass. agric. Exp. Sta.* 305. (Rep. for 1932-33), 11.
HAESSNER, —. 1887. Untersuchungen über den Nährstoffgehalt in den Wurzeln und Körnern

der Gerste und Verhalten desselben zu den im Boden vorhandenen assimilierbaren Pflanzennährstoffen. [quoted by Helmkampf, 1892].
HALAIS, P. 1933. Part III. Biochemistry. *Rep. Sug. Cane Res. Sta. Mauritius*, 3, 47-62.
———— 1937. Part II—Bio-chemistry. I. Soil studies. *Rep. Sug. Cane Res. Sta. Mauritius*, 7, 19-29.
HALE, J. B. 1945. Deficiency diseases of the sugar beet. Agric. Res. Coun., pp. 8. Unpublished report, duplicated for private circulation. A.R.C. 7828, pp. 8.
HALL, A. D. 1905. The analysis of the soil by means of the plant. *J. agric. Sci.*, 1, 65-88.
HAMBIDGE, G. (edited by). 1941. Hunger signs in crops. A symposium. American Society of Agronomy and National Fertilizer Association, Washington, D.C. pp. xiv. + 327.
HANAMANN, J. 1904. Beiträge zur Ausbildung einer Methode behufs Feststellung des Düngungsbedürfnisses des Ackerbodens durch die Pflanzenanalyse. *Z. landw. VersWes. Öst.*, 7, 805-818.
HANCE, F. E. 1936. Soil and plant material analyses by rapid chemical methods. *Hawaii. Plant. Rec.*, 40, 189-299.
———— 1937. Soil and plant material analyses by rapid chemical methods.—II. *Hawaii. Plant Rec.*, 41, 135-186.
———— 1941. Soil and plant material analyses by rapid chemical methods.—III. *Hawaii. Plant. Rec.*, 45, 265-296.
HANSEN, C. J. 1945. Boron content of olive leaves. *Proc. Amer. Soc. hort. Sci.*, 46, 78-80.
HARDY, F. 1937. Cacao soil investigations. (2) Marginal leaf-scorch of cacao. Its relationship to soil potash deficiency. (With a note on the ecology of cacao thrips.) *Rep. Cacao Res. Trinidad*, 6, 13-24.
————, MCDONALD, J. A., and RODRIGUEZ, G. 1935. Leaf analysis as a means of diagnosing nutrient requirements of tropical orchard crops. *J. agric. Sci.*, 25, 610-627.
———— and RODRIGUEZ, G. 1935. Grapefruit investigations in Trinidad. *Trop. Agriculture, Trin.*, 12, 205-215.
HARRINGTON, J. F. 1944. Some factors influencing the reliability of plant tissue testing. *Proc. Amer. Soc. hort. Sci.*, 45, 313-317.
HART, M. L. T., and VAN DER PAAUW, F. 1942. (Potash fertilizing on meadows.) *Meded. Direct. Landbouw. Landbouwvoorlichtingsdienst* 30, 1-42. [quoted in *Chem. Abs.*, 38, 4742.]
HASELHOFF, E. 1918. Über die Ermittelung des Düngebedürfnisses des Bodens. *Fühlings landw. Ztg*, 67, 193-204.
HEINICKE, A. J., REUTHER, W., and CAIN, J. C. 1942. Influence of boron application on preharvest drop of McIntosh apples. *Proc. Amer. Soc. hort. Sci.*, 40, 31-34.
HEINRICH, R. 1882. Grundlagen zur Beurtheilung der Ackerkrume in Beziehung auf landwirthschaftliche Production. [quoted by Helmkampf; 1892; Stahl-Schröder 1904].
HELLRIEGEL, —. 1867. Uber das Kalibedürfnis der Gerste. *Wochenbl. Ann. Landw. for* 1867. 299 ff. [quoted in *Jber. Fortschr. Agrik. Chem.*, 10, 117-119].
———— 1869. Bedeutung der chemischen Untersuchung der Ernteproducte, namentlich der Aschenanalysen, für die Beurtheilung der Menge und des gegenseitigen Verhältnisses der im Boden vorhandenen aufnehmbaren Pflanzennährstoffe. *Landw. VersSta.*, 11, 136-140.
HELMKAMPF, A. 1892. Untersuchungen über die Feststellung des Düngungsbedürfnisses der Ackerböden durch die Pflanzenanalyse. *J. Landw.*, 40, 85-183.
HERSCHLER, A. 1933. Analysen von Rebblättern zur Feststellung des Nährstoffbedürfnisses des Bodens und zur Erkennung von Ernährungsstörungen. *Arb. biol. Reichsanst.*, 20, 633-666.
HESTER, J. B. 1940. A satisfactory grinder for preparing plant tissue for rapid chemical tests. *J. Amer. Soc. Agron.*, 32, 549.
———— 1941. Soil and plant tests as aids in soil fertility programs. *Com. Fertil.*, 63 (5), 10-16, 18, 20. *Com. Fertil. Yearb. for* 1941, 31-39.
————, BLUME, J. M., and SHELTON, F. A. 1937. Rapid chemical tests for Coastal Plain soils. *Bull. Va Truck Exp. Sta.* 95, 1433-1487.

HIBON, J. 1944. Entrétien ou rétablissement de la fertilité au vignoble. (Le diagnostic foliaire.) *Fruits et Primeurs*, 14, 28-29.
HILGEMAN, R. H. 1941. Nitrogen uptake by grapefruit trees in the Salt River Valley. *Proc. Amer. Soc. hort. Sci.*, 39, 119-124.
————, SMITH, J. G., and DRAPER, G. E. 1940. A preliminary note on nitrogen assimilation by citrus trees. *Proc. Amer. Soc. hort. Sci.*, 37, 58-61.
HILL, H. 1938. Plant nutrition with special reference to deficiencies. *Ph. D. Thesis, Univ. Lond.*, pp. 171.
———— 1940. Progress report, magnesium deficiency, Frelighsburg. *Rep. pomol. Soc. Quebec*, 46, 8-11.
———— 1941. Progress report—magnesium deficiency in apple orchards of Frelighsburg district. *Rep. pomol. Soc. Quebec*, 47, 12-15.
———— 1943. Malnutrition symptoms and plant tissue tests of vegetable crops. *Better Crops with Plant Food*, 27 (5), 6-10, 44, 45.
———— and JOHNSTON, F. B. 1940. Magnesium deficiency of apple trees in sand culture and in commercial orchards. *Sci. Agric.*, 20, 516-525.
HIRST, C. T., and GREAVES, J. E. 1944. The nitrogen and mineral contents of sugar beet sections. *Soil Sci.*, 58, 25-34.
HOAGLAND, D. R., and ARNON, D. I. 1941. Physiological aspects of availability of nutrients for plant growth. *Soil Sci.*, 51, 431-444.
———— and CHANDLER, W. H. 1933. Some effects of deficiencies of phosphate and potassium on the growth and composition of fruit trees, under controlled conditions. *Proc. Amer. Soc. hort. Sci.*, 29, 267-270.
———— ———— and STOUT, P. R. 1937. Little-leaf or rosette of fruit trees VI. Further experiments bearing on the cause of this disease. *Proc. Amer. Soc. hort. Sci.*, 34, 210-211.
———— and MARTIN, J. C. 1933. Absorption of potassium by plants in relation to replaceable, non-replaceable, and soil solution potassium. *Soil Sci.*, 36, 1-33.
HODGKISS, W. S., HAGEMAN, R. H., and MCHARGUE, J. S. 1942. The amount of boron absorbed by soybean plants and its effect on their growth. *Plant Physiol.*, 17, 652-660.
HOFFER, G. N. 1926. Testing corn stalks chemically to aid in determining their plant food needs. *Bull. Ind. agric. Exp. Sta.* 298 (revised 1930), 1-31.
———— and TROST, J. F. 1923. The accumulation of iron and aluminium compounds in corn plants and its probable relation to root rots. II. *J. Amer. Soc. Agron.*, 15, 323-331.
HOFFMAN, M. 1913. Der Einfluss der Düngung auf die Wiese. *Mitt. dtsch. LandwGes.*, 28, 650-654.
———— 1917. Zur Frage der Ermittlung des Düngerbedürfnisses einer Wiese bezw. eines Ackers, insonderheit bezüglich des Kaligehaltes. *Mitt. dtsch. LandwGes.*, 32, 679-682.
HOLMES, R. L. 1939. Preliminary studies on the correlation of cane juice analyses with soil analyses. *Proc. int. Soc. Sug. Cane Tech.*, 6, 314-319.
HOOD, S. L., PARKS, R. Q., and HURWITZ, C. 1944. Mineral contamination resulting from grinding plant samples. *Industr. Engng Chem., Anal. Ed.* 16, 202-205.
HUNTER, A. S., TOTH, S. J., and BEAR, F. E. 1943. Calcium-potassium ratios for alfalfa. *Soil Sci.*, 55, 61-72.
HUNTER, J. G. 1942. A chlorosis of bracken due to manganese deficiency. *Nature, Lond.*, 150, 578-579.
ILJIN, W. S. 1943. Der Stoffwechsel bei der Weinrebe während der Kalkchlorose. *Gartenbauwiss.*, 17, 338-381.
INGALLS, R. A., and SHIVE, J. W. 1931. Relation of H-ion concentration of tissue fluids to the distribution of iron in plants. *Plant Physiol.*, 6, 103-125.
INGRAM, J. M., STAIR, E. C., and HARTMAN, J. D. 1943. Field response of tomatoes to large applications of phosphates. *Proc. Amer. Soc. hort. Sci.*, 42, 529-534.
VAN ITALLIE, T. B. 1935. De fosforzuur- en kaligehalten van gras als aanwijzing voor de fosforzuur- en kaligesteldheid van grasland. *Landbouwk. Tijdschr., 's Grav.* 47, 17-34.
———— 1936. Hooghalensche ziekte en de samenstelling van graanplanten. [German summary.] *Landbouwk. Tikjdschr. 's Grav.*, 48, 125-142.

——— 1937. Magnesiummangel und Ionenverhältnisse in Getreidepflanzen. *Bodenk. PflErnähr.*, 5, 303-334.

Jacob, A. 1929. Die chemische Untersuchung des Blattes als diagnostisches Mittel zur Bestimmung des Nährstoffbedarfes des Weinstocks. *Z. angew. Chem.*, 42, 257-262.

Jacobson, H. G. M., and Swanback, T. R. 1932. Manganese content of certain Connecticut soils and its relation to the growth of tobacco. *J. Amer. Soc. Agron.*, 24, 237-245.

Jacobson, L. 1945. Iron in the leaves and chloroplasts of some plants in relation to their chlorophyll content. *Plant Physiol.*, 20, 233-245.

Jakuškin, I. 1915. Easily extractable phosphorus in the plant and the adequacy of its uptake of phosphoric acid. [Russian, with French summary.] *Russ. J. exp. Agric.* 16, 118-139.

Januszewski, Z. 1895. Ueber die Pflanzen- und die Bodenanalyse in ihrer Bedeutung für die Bestimmung der Bodenqualität. Inaug-Diss., Leipzig. [quoted in 1899: *Biederm. Zbl.*, 28, 77-79.]

Johnson, L. H., Lindstrom, H. V., and Gortner, R. A. 1943. Sulphur in plants. I. Effect of application of gypsum and sodium selenate on sulphur distribution and manganese, iron, and copper contents of lucerne. *Arch. Biochem.*, 2, 435-441. [quoted in *Brit. Chem. Physiol. Abs. A III*, 1944, p. 153].

Jones, H. E. 1941. Plant tissue tests as an aid in growing alfalfa for studies in animal nutrition. *Proc. nat. Jt Comm. Fert. Appl.*, 17, 43.

——— and Scarseth, G. D. 1944. The calcium-boron balance in plants as related to boron needs. *Soil Sci.*, 57, 15-24.

Jones, J. O., Nicholas, D. J. D., and Wallace, T. 1944. Experiments on the control of magnesium deficiency in greenhouse tomatoes. Progress report I. *Rep. agric. hort. Res. Sta. Bristol for* 1943, 48-53.

——— ——— ——— and Jefferiss, A. 1945. Experiments on the control of magnesium deficiency in glasshouse tomatoes. Progress report II. *Rep. agric. hort. Res. Sta. Bristol for* 1944, 61-71.

——— and Plant, W. 1943. Note on the composition of leaves from potato manurial experiment. *Rep. agric. hort. Res. Sta. Bristol for* 1942. 44-45.

——— and Russell, R. D. 1945. Mineral deficiency survey of Somersetshire. Agric. Res. Coun. Unpublished report, duplicated for private circulation. A.R.C. 7866. pp. 13.

Jones, J. P. 1929. Deficiency of magnesium the cause of a chlorosis in corn. *J. agric. Res.*, 39, 873-892.

Jones, W. N. 1938. On the occurrence of needle fusion in pines in the south of England. *Emp. For. J.*, 17, 244-246.

Jones, W. W. 1944. N control program. *Citrus leaves*, 24 (5), 10-11. [quoted in *Chem. Abs.*, 38, 4366].

Joulie, H. 1876. Guide pour l'achat et l'emploi des engrais chimiques. 5me Edition. 2me Tirage. Société Anonyme des Produites Chimiques Agricoles, Paris and Bordeaux, pp. 487.

——— 1889. Sur la transformation des terres de la ferme D'Arcy. *J. Agric., Paris*, 24 (1), 89-95.

Kalin, E. W. 1943. pH of extracted cell sap and phosphorus content of young tomato plants growing on varying levels of phosphorus. *Proc. Amer. Soc. hort. Sci.*, 43, 235-238.

Kauter, A. 1935. Der Aschengehalt des Heugrases in seiner Abhängigkeit von Pflanzenbestand und Bodenreaktion. [French summary.] *Landw. Jb. Schweiz*, 49, 69-86.

Keiller, P. A. 1939. Note on the analysis of leaves from tea bushes affected by " witches' broom". *Tea Quart.*, 12, 96-97.

Kelley, W. P., and Brown, S. M. 1928. Boron in the soils and irrigation waters of southern California and its relation to citrus and walnut culture. *Hilgardia*, 3, 445-458.

Kidson, E. B. 1942. An ash skeleton method for the diagnosis of magnesium and potassium deficiencies in apple leaves and for the determination of their distribution in the leaf. *N.Z.J. Sci. Tech.*, 24, 140B-145B.

KIDSON, E. B., ASKEW, H. O., and CHITTENDEN, E. 1940. Magnesium deficiency of apples in the Nelson District, New Zealand. *N.Z.J. Sci. Tech.*, 21, 305A-318A. *J. Pomol.*, 18, 119-134.

——— ——— ——— 1943. The value of magnesium compounds for the control of magnesium deficiency of apple trees. *N.Z.J. Sci. Tech.*, 25, 31A-42A.

KLEMEN, R. 1931. Ueber vergleichende Rebblattanalysen in verschiedenen Weinbergslagen zu bestimmten Zeiträumen. *Mitt. Lab. st. VersSta. Maribor.* [quoted by Herschler, 1933, from *Das Weinland*, 3, 90, 1931].

KNUDSON, L., and GINSBURG, S. 1921. Suggestions with respect to the measurement of osmotic pressure. *Amer. J. Bot.*, 8, 164-170.

KOSCELECKIĬ, A. 1909. On the question of soil fertility in relation to phosphoric acid. [Russian.] *Russ. J. exp. Agric.*, 10, 321-354.

KOSUTANY, T. 1897. Untersuchungen über die Entstehung des Pflanzeneiweisses. *Landw. VersSta.*, 48, 13-32.

KRIEL, H. T. 1941. A study of the effect of excess manganese on iron and chlorophyll content and growth of tomato plants. Thesis, Univ. Calif. [Quoted by Bennett, 1945.]

KRÜGER, W., WIMMER, G., and LÜDECKE, H. 1931. Können Kali- und Stickstoffmangel durch chemische Reaktionen in Teilen von lebenden Pflanzen festgestellt werden? *Ernähr. Pfl.*, 27, 425-429, 450-452.

LAGATU, H. 1940. Importance et difficultés de la fumure potassique des vignes méridionales. Montpellier. [quoted by Hibon, 1944].

——— and MAUME, L. 1924. Évolution remarquablement régulière de certains rapports physiologiques (chaux, magnésie, potasse) dans les feuilles de la vigne bien alimentée. *C. R. Acad. Sci. Paris*, 179, 782-785. 1933. *Ann. Éc. Agric. Montpellier*, 22, 257-260.

——— ——— 1924a. Étude, par l'analyse périodique des feuilles, de l'influence des engrais de chaux, de magnésie et de potasse sur la vigne. *C. R. Acad. Sci., Paris*, 179, 932-934. 1933. *Ann. Éc. Agric. Montpellier*, 22, 260-263.

——— ——— 1925. Relation linéaire entre les quantités successives d'acide phosphorique et d'azote contenues dans la feuille de la vigne bien alimentée. *C. R. Acad. Sci., Paris*, 180, 1179-1181. 1933. *Ann. Éc. Agric. Montpellier*, 22, 263-266.

——— ——— 1926. Diagnostic de l'alimentation d'un végétal par l'évolution chimique d'une feuille convenablement choisie. *C. R. Acad. Sci., Paris*, 182, 653-655. 1933. *Ann. Éc. Agric. Montpellier*, 22, 266-268.

——— ——— 1927. Examen critique des conditions et des résultats du contrôle alimentaire de la vigne. *C. R. Acad. Agric. Fr.*, 13, 548-553.

——— ——— 1927a. Méthode de contrôle chimique du mode d'alimentation de la vigne. *C.R. Acad. Agric. Fr.*, 13, 439-442.

——— ——— 1927b. Sur l'absorption de l'acide phosphorique par la vigne et sur son rôle physiologique. *C.R. Acad. Agric. Fr.*, 13, 443-448.

——— ——— 1927b. Sur l'absorption de la potasse par la vigne et sur son rôle physiologique. *C.R. Acad. Agric. Fr.*, 13, 448-452.

——— ——— 1927d. Sur l'absorption de l'azote par la vigne et sur son rôle physiologique. *C.R. Acad. Agric. Fr.*, 13, 452-455.

——— ——— 1927e. Contrôle du mode d'alimentation d'une plante pérenne (vigne) dans le sol donné recevant une fumure donnée. *C.R. Acad. Sci., Paris*, 184, 229-231. 1933. *Ann. Éc. Agric. Montpellier*, 22, 268.

——— ——— 1928. Antagonisme du calcaire à l'égard de l'absorption de la potasse par la vigne. *Progr. agric. vitic.*, 90, 492-497.

——— ——— 1928a. Le diagnostic foliaire appliqué au contrôle de l'alimentation d'une vigne de coteau avec ou sans fumure. *C.R. Acad. Agric. Fr.*, 14, 762-776.

——— ——— 1929. Le diagnostic foliaire et son degré de sécurité. *C.R. Acad. Sci., Paris*, 188, 1062-1064. 1933. *Ann. Éc. Agric. Montpellier*, 22, 271-274.

——— ——— 1930. Évolution chimique comparée des feuilles de la vigne prélevées à des hauteurs différentes sur les rameaux. *C.R. Acad. Sci., Paris*, 190, 1137-1139. 1933. *Ann. Éc. Agric. Montpellier*, 22, 277-279.

——— ——— 1930a. Observation, par le diagnostic foliaire, du phénomène de remplacement physiologique mutuel de deux bases : chaux et potasse. *C. R. Acad. Sci. Paris*, 190, 389-391. 1933. *Ann. Éc. Agric. Montpellier*, 22, 274-276.
——— ——— 1930b. Le diagnostic foliaire de la pomme de terre. Premier mémoire. *Ann. Éc. Agric. Montpellier*, 20, 219-281. *Ann. Sci. agron., Paris*, 47, 595-653.
——— ——— 1930c. Observation, par le diagnostic foliaire, de l'influence de la température sur le mode d'alimentation d'un végétal. *C.R. Acad. Sci., Paris*, 190, 1516-1518. 1933. *Ann. Éc. Agric. Montpellier*, 22, 279-282.
——— ——— 1930d. Réponse explicite du diagnostic foliaire, alors que les autres moyens d'observation restent muets. *C.R. Acad. Sci., Paris*, 191, 579-580. 1933. *Ann. Éc. Agric. Montpellier*, 22, 282-284.
——— ——— 1930e. Absorption comparée de différents engrais azotés par une vigne au cours de la même année. *Progr. agric. vitic.*, 93, 399-403, 430-435.
——— ——— 1931. Variation des rapports physiologiques entre les constituants minéraux d'une espèce végétale. *C. R. Acad. Sci., Paris*, 193, 103-106. 1933. *Ann. Éc. Agric. Montpellier*, 22, 284-287.
——— ——— 1932. Application du diagnostic foliaire : il suggère, contrôle et limite le redressement alimentaire d'une vigne mal nourrie. *C. R. Acad. Sci., Paris*, 194, 812-814. 1933. *Ann. Éc. Agric. Montpellier.*, 22, 291-294.
——— ——— 1932a. La feuille peut-elle accepter une surcharge d'aliment minéral sans profit pour le développement du végétal ? *C. R. Acad. Sci., Paris*, 194, 933-935. 1933. *Ann. Éc., Agric. Montpellier*, 22, 294-297.
——— ——— 1932b. Un cas d'absolue nécessité d'engrais potassique. *Progr. agric. vitic.*, 97, 576-581.
——— ——— 1932c. Étude, par le diagnostic foliaire, des effets physiologiques du chaulage. *C. R. Acad. Agric. Fr.*, 18, 443-452.
——— ——— 1933. Le diagnostic foliaire de la pomme de terre. Deuxième mémoire. *Ann. Éc. Agric. Montpellier*, 22, 50-158. *Ann. Agron., Paris*, N.S.2, 306-362 ; 3, 1-52.
——— ——— 1933a. Sur les variations alimentaires des végétaux cultivées, en dehors de toute intervention d'engrais, dans les conditions de la pratique agricole. *C. R. Acad. Sci., Paris*, 197, 1558-1560. *Ann. Éc. Agric. Montpellier*, 22, 303-306.
——— ——— 1933b. Composition comparée, chez la vigne, de feuilles homologues prises respectivement sur des souches fructifères et sur des souches privées de leurs grappes. *C. R. Acad. Sci., Paris*, 196, 1168-1170. *Ann. Éc. Agric. Montpellier*, 22, 297-300.
——— ——— 1933c. Composition comparée de la matière sèche des feuilles homologues des rameaux fructifères et des rameaux naturellement stériles de la vigne. *C. R. Acad. Sci., Paris*, 196, 1445-1447. *Ann. Éc. Agric. Montpellier*, 22, 300-303.
——— ——— 1934. Variations qualitatives et quantitatives de l'alimentation NPK d'une même espèce végétale dans un même sol, en dehors de toute intervention d'engrais. *C. R. Acad. Agric. Fr.*, 20, 443-448.
——— ——— 1934a. Examen critique du diagnostic foliaire. *C. R. Acad. Agric. Fr.*, 20, 246-257.
——— ——— 1934b. Action d'un même engrais simple annuel sur l'alimentation NPK d'une même espèce végétale au cours de quatre années successives de culture dans le même sol. *C. R. Acad. Agric. Fr.*, 20, 549-563.
——— ——— 1934c. Recherche, par le diagnostic foliaire, de l'équilibre optimum d'alimentation NPK chez une plante cultivée. *C. R. Acad. Agric. Fr.*, 20, 631-644.
——— ——— 1935. Sur la cinématique de la chaux, de la magnésie et de leur rapport physiologique dans la feuille du tabac ; méthode des relais foliaires. *C. R. Acad. Sci., Paris*, 200, 881-883. 1936. *Ann. Éc. Agric. Montpellier*, 24, 7-10.
——— ——— 1935a. Diagnostic foliaire de tabac : influence comparée des scories de déphosphoration, du superphosphate et du basiphosphate sur l'équilibre NPK. *C. R. Acad. Sci., Paris*, 200, 502-504. 1936. *Ann. Éc. Agric. Montpellier*, 24, 3-6.
——— ——— 1935b. Sur les variations de la somme $N+P_2O_5+K_2O$ pour 100 de matière sèche de la feuille d'une plante cultivée. *C. R. Acad. Agric. Fr.*, 21, 85-92.

LAGATU, H., and MAUME, L. 1935c. Détermination, par le diagnostic foliaire, d'un cas d'inhibition de la potasse. *C. R. Acad. Agric. Fr.*, 21, 232-241.
——— ——— 1935d. Démonstration, par le diagnostic foliaire, de l'efficacité du fumier pour vaincre l'inhibition de la potasse. *C. R. Acad. Agric. Fr.*, 21, 396-404.
——— ——— 1935e. Variations des rapports physiologiques en corrélation avec la maladie du feu sauvage chez la feuille du tabac. *C. R. Acad. Sci., Paris*, 201, 374-376. 1936. *Ann. Éc. Agric. Montpellier*, 24, 11-13.
——— ——— 1936. Variations qualitatives et quantitatives de l'alimentation NPK d'une même espèce végétale dans un même sol, en dehors de toute intervention d'engrais. *Progr. agric. vitic.*, 105, 353-356.
——— ——— 1936a. Dans quelle mesure les variations atmosphériques peuvent-elles, sous le climat méditerranéan, modifier chez une vigne les rapports physiologiques et les quantitées absorbées d'azote, d'acide phosphorique et de potasse ? *C. R. Acad. Agric. Fr.*, 22, 363-382. *Ann. Éc. Agric. Montpellier*, 24, 159-179.
——— ——— 1936b. Vigne et apports calciques. *C. R. Acad. Agric. Fr.*, 22, 478-494. *Ann. Éc. Agric. Montpellier*, 24, 180-199.
——— ——— 1936c. Sur la possibilité de variations de sens opposés et de grande amplitude, au cours d'une même année, pour l'équilibre NPK chez la feuille d'une plante cultivée. *C. R. Acad. Sci., Paris*, 202, 1550-1553. *Ann. Éc. Agric. Montpellier*, 24, 200-204.
——— ——— 1936d. Contribution a l'étude de l'influence alimentaire du basiphosphate sur la vigne. *C. R. Acad. Agric. Fr.*, 22, 1132-1138. 1937. *Ann. Éc. Agric. Montpellier*, 24, 353-360.
——— ——— 1936e. Contribution a l'étude de l'influence alimentaire du superphosphate sur la vigne. *C. R. Acad. Agric. Fr.*, 22, 1018-1031. 1937. *Ann. Éc. Agric. Montpellier*, 24, 339-351.
——— ——— 1937. Sur la détermination chimique de la plante cultivée. *C. R. Acad. Sci., Paris*, 205, 549-552. 1938. *Ann. Éc. Agric. Montpellier*, 25, 5-8.
——— ——— 1937a. L'acide phosphorique dans les équilibres physiologiques NPK de la feuille de la vigne. *C. R. Acad. Agric. Fr.*, 23, 96-102. *Ann. Éc. Agric. Montpellier*, 24, 361-367.
——— ——— 1937b. Possibilité de mesurer séparément, à tout moment de la végétation, l'effect nutritif et l'effet améliorant d'un apport d'engrais. *C. R. Acad. Sci., Paris*, 204, 535-538. *Ann. Éc. Agric. Montpellier*, 24, 377-380.
——— ——— 1937c. Interêt que présente pour l'agriculture la mesure séparé de l'effet nutritif et de l'effet améliorant d'un apport d'engrais. *C. R. Acad. Sci., Paris*, 204, 939-941. *Ann. Éc. Agric. Montpellier*, 24, 381-390.
——— ——— 1938. Mesures de biochimie agricole sur des rameux de la vigne. *C. R. Acad. Sci., Paris*, 206, 1237-1240.
——— ——— 1938a. Sur la sensibilité du diagnostic foliaire pour décaler une absorption d'engrais par la vigne. *C. R. Acad. Agric. Fr.*, 24, 615-624.
——— ——— 1938b. Mesures de biochimie agricole sur des rameaux de la vigne. *Ann. Éc. Agric. Montpellier*, 25, 137-173.
——— ——— 1938c. La composition NPK des feuilles d'un rameau de vigne aramon diffère-t-elle selon que ce rameau est plus ou moins fructifère ? *C. R. Acad. Sci., Paris*, 207, 552-555.
——— ——— 1939. Influence de la nature du porte-greffe sur le mode d'alimentation NPK de la vigne greffé. *C. R. Acad. Sci., Paris*, 209, 281-284.
——— ——— 1943. Détermination, par la plante cultivée, de la valeur nutritive d'un milieu cultural. *C. R. Acad. Sci., Paris*, 216, 753-755.
——— ——— and CROS, L. 1932. Étude des variations de la teneur en azote en des points très localisés du feuillage de la vigne. *C. R. Acad. Sci., Paris*, 194, 679-681. 1933. *Ann. Éc. Agric. Montpellier*, 22, 257-306.
LANGE, W. 1926. Beiträge zur Bestimmung des Düngebedürfnisses eines Bodens vermittels Pflanzen- und Bodenanalyse. *Z. PflErnähr. Dung. A.*, 6, 193-228.

LARGE, E. C. 1944. Rust : potato killer No. 2. *Fmr. & Stk-Breed.*, 58, 1247.
———— 1945. Potato 'rust' or potash deficiency. Agric. Res. Coun. Unpublished report duplicated for private circulation. A.R.C. 7849, 37-43.
———— 1945a. Identification of mineral deficiency symptoms in field beans by leaf-analysis methods, and relation to Chocolate Spot. Agric. Res. Coun. Unpublished report duplicated for private circulation. A.R.C. 7849, 45-46.
LARSON, C. A. 1933. Effect of fertilizers on irrigated Ephrata fine sand and apple tree response in the Wenatchee orchard district. *J. Amer. Soc. Agron.*, 25, 633-652.
LAWES, J. B. and GILBERT, J. H. 1895. The Rothamsted experiments ; being an account of some of the results of the agricultural investigations conducted at Rothamsted, in the field, the feeding shed, and the laboratory, over a period of fifty years. Reprinted from *Trans. Highland agric. Soc. Scotland, 5th. Ser.*, 7, 1-354 by William Blackwood & Sons, Edinburgh and London.
LAZURSKIĬ, A. V. 1939. Determination of requirements of plants for nitrogen and phosphorus by the compensation method. [Russian]. *Dokl. Akad. s-kh. Nauk for* 1939 (1), 6-13.
———— 1940. Further improvement of the compensation method for determination of the requirements of plants for nitrogen and phosphorus. [Russian]. *Dokl. Akad. s-kh. Nauk for* 1940, (6), 31-35.
LEE, H. A. and MCHARGUE, J. S. 1928. The effect of a manganese deficiency on the sugar cane plant and its relationship to Pahala blight of sugar cane. *Phytopathology*, 18, 775-786,
LEEPER, G. W. 1941. Manganese deficiency and accumulation of nitrates in plants. *J. Aust. Inst. agric. Sci.*, 7, 161-162.
LEVITT, E. C. and NICHOLSON, R. I. 1941. Manganese deficiency in citrus in New South Wales coastal districts. *Agric. Gaz. N.S.W.*, 52, 283-286.
LIEBICH, H. 1941. A quantitative chemical investigation of the iron in the chloroplasts and other cell components of *Spinacia oleracea*. *Z. Bot.*, 37, 129-157. [quoted in *Chem. Abs.*, 37, 2774, from *Chem. Zbl.*, 1942, I, 884].
LIEBIG, G. F. JR., VANSELOW, A. P. and CHAPMAN, H. D. 1943. Effects of gallium and indium on the growth of citrus plants in solution cultures. *Soil. Sci.*, 56, 173-185.
VON LIEBIG, J. 1840. Organic chemistry in its applications to agriculture and physiology. [Edited from the notes of the author by Lyon Playfair.] Taylor and Walton, London : pp. xvi+387.
———— 1863. The natural laws of husbandry. [Edited by John Blyth]. Walton & Maberley, London, pp. xx+416.
LIEBSCHER, —, KRETSCHMER, —, von SEELHORST, — and WILMS, J. 1898. Versuche zur Ermittelung des Düngerbedürfnisses des Ackerbodens B. Ermittelung der Düngerbedürftigkeit des Bodens aus der Zusammensetzung der Erntetrockensubstanz. *J. Landw.*, 46, 367-412.
LIECHTI, P., and RITTER, E. 1917. Ermittlung des Phosphorsäure- und Kalibedürfnisses der Wiesenböden aus dem Gehalt der Erntesubstanzen an diesen Stoffen. *Landw. Jb. Schweiz*, 31, 533-553.
LILLELAND, O. 1931. Does potassium increase the sugar content of prunes ? *Proc. Amer. Soc. hort. Sci.*, 27, 15-18.
———— 1933. Experiments in K and P deficiencies with fruit trees in the field. *Proc. Amer. Soc. hort. Sci.*, 29, 272-276.
————, and BROWN, J. G. 1939. The potassium nutrition of fruit trees II. Leaf analyses. *Proc. Amer. Soc. hort. Sci.*, 36, 91-98.
———— ————. 1940. The phosphate nutrition of fruit trees II. Continued response to phosphate applied at the time of planting. *Proc. Amer. Soc. hort. Sci.*, 37, 53-57.
———— ———— 1941. The potassium nutrition of fruit trees III. A survey of the K content of peach leaves from one hundred and thirty orchards in California. *Proc. Amer. Soc. hort. Sci.*, 38, 37-48.
———— ———— 1942. The phosphate nutrition of fruit trees IV. The phosphate content of peach leaves from 130 orchards in California and some factors which may influence it. *Proc. Amer. Soc. hort. Sci.*, 41, 1-10.

LILLELAND, O., BROWN, J. G. and CONRAD, J. P. 1942. The phosphate nutrition of fruit trees III. Comparison of fruit tree and field crop responses on a phosphate deficient soil. *Proc. Amer. Soc. hort. Sci.*, 40, 1-7.
LINDNER, R. C. 1943. Arsenic injury of peach trees. *Proc. Amer. Soc. hort. Sci.*, 42, 275-279.
———— 1944. Rapid analytical methods for some of the more common inorganic constituents of plant tissues. *Plant Physiol.*, 19, 76-89.
————, and HARLEY, C. P., 1942. A rapid method for the determination of nitrogen in plant tissue. *Science* (*N.S.*), 96, 565-566.
———— ———— 1944. Nutrient interrelations in lime-induced chlorosis. *Plant Physiol.*, 19, 420-439.
LINEBERRY, R. A. and BURKHART, L. 1943. Nutrient deficiencies in the strawberry leaf and fruit. *Plant Physiol.*. 18, 324-333.
———— ————, and COLLINS, E. R. 1944. Fertilizer requirements of strawberries on new land in North Carolina. *Proc. Amer. Soc. hort. Sci.*, 45, 283-292.
LOEHWING, W. F. 1928. Calcium, potassium, and iron balance in certain crop plants in relation to their metabolism. *Plant Physiol.*, 3, 261-275.
LÖHNIS, M. P. 1936. Wat veroorzaakt kwade harten in erwten? *Tijdschr. PlZiekt.*, 42, 159-167.
LORENZ, O. A. 1942. Internal breakdown of table beets. *Mem. Cornell agric. Exp. Sta.* 246. 1-42.
———— 1944. Studies on potato nutrition: I. The effects of fertilizer treatment on the yield and composition of Kern County potatoes. *Amer. Potato J.*, 21, 179-192.
———— 1944a. Studies on potato nutrition II. Nutrient uptake at various stages of growth by Kern County potatoes. *Proc. Amer. Soc. hort. Sci.*, 44, 389-394.
———— and MINGES, P. A. 1942. Nutrient absorption by a summer crop of lettuce in Salinas Valley, California. *Proc. Amer. Soc. hort. Sci.*, 40, 523-527.
LOTT, R. V. 1942. Effect of nitrate of soda on development of the Halehaven peach. *Bull. Ill. agric. Exp. Sta.* 493, 323-384.
LOWRY, M. W. and TABOR, P. 1931. Sap for analysis by bleeding corn plants. *Science* (*N.S.*), 73, 453.
———— HUGGINS, W. C., and FORREST, L. A. 1936. The effect of soil treatment on the mineral composition of exuded maize sap at different stages of development. *Bull. Ga Exp. Sta.* 193, 1-28.
————, and TABOR, P. 1931. Sap for analysis by bleeding corn plants. *Science* (*N.S.*), 73, 453.
LUNDEGÅRDH, H. 1931. Studier över stråsädens näringsupptagande samt dettas betydelse för tillväxten och för uppkomsten av icke-parasitära sjukdomar. [English summary]. *Medd. CentAnst. Försöksv. Jordbr. Stockh.* 403, 1-146. *K. LandtbrAkad. Handl., Stockh.*, 70, 1021-1164.
———— 1932. Die Nährstoffaufnahme der Pflanze. Gustav Fischer, Jena, pp. viii+374.
———— 1934. Markbeskaffenhet och gödslingsbehov. [English summary] *K. LandtbrAkad. Handl., Stockh.*, 73, 225-289. *Medd. CentAnst. Försöksv. Jordbr., Stockh*, 444, 225-289.
———— 1935. The influence of the soil upon the growth of the plant. *Soil Sci.*, 40, 89-101.
———— 1938. The triple-analysis method of testing soil fertility and probable crop reaction to fertilization. *Soil. Sci.*, 45, 447-454.
———— 1939. Trippelanalys-metodiken för bestämning av gödslingsbehovet. [German summary]. *K. LandtbrAkad. Handl., Stockh.*, 78, 157-168.
———— 1941. Die Tripelanalyse. Theoretische und praktische Grundlagen einer pflanzenphysiologischen Methode zur Bestimmung des Düngerbedürfnisses des Ackerbodens. *LantbrHögsk. Ann.*, 9, 127-221.
———— 1934. Leaf analysis as a guide to soil fertility. *Nature, Lond.*, 151, 310-311.
———— 1945. Absorption, transport and exudation of inorganic ions by the roots. *Ark. Bot.*, 32A (12), 1-139.
LUTMAN, B. F. and WALBRIDGE, N. L. 1929. The role of magnesium in the aging of plants. *Bull. Vt agric. Exp. Sta.* 296, 1-48.

LYMAN, C. and DEAN, L. A. 1942. Zinc deficiency of pineapples in relation to soil and plant composition. *Soil Sci.*, 54, 316-324.
LYON, C. B., BEESON, K. C. and ELLIS, G. H. 1943. Effects of micro-nutrient deficiencies on growth and vitamin content of the tomato. *Bot. Gaz.*, 104, 495-514.
MCCOLLAM, M. E. 1943. Asking the plant what food it needs. *Better Crops with Plant Food*, 27 (8), 11-12.
———— 1944. Leaf analysis—a guide to better crops. *Better Crops with Plant Food*, 28 (10), 11-14, 42.
MCCOOL, M. M. 1926. Relation of soil to plant cell sap. Use of fertilizers lowers freezing point of cell sap—phosphorus content of plant affected. *Quart. Bull. Mich. agric. Exp. Sta.*, 9, 60-64.
———— and MILLAR, C. E. 1917. The water content of the soil and the composition and concentration of the soil solution as indicated by the freezing-point lowerings of the roots and tops of plants. *Soil. Sci.*, 3, 113-138.
———— and WELDON, M. D. 1928. The effect of soil type and fertilization on the composition of the expressed sap of plants. *J. Amer. Soc. Agron.*, 20, 778-792.
MCDONALD, J. A. 1933. Progress of some detailed investigations. III.—Chemical composition of the leaves of cacao in relation to environmental growth conditions, and with special reference to thrips attack. *Rep. Cacao Res., Trinidad*, 2, ix-xii.
———— 19333a. A sensitive pot test for phosphate deficiency in soils. *Trop. Agriculture, Trin.*, 10, 108-111.
———— 1934. A study of the relationship between nutrient supply and the chemical composition of the cacao tree. *Rep. Cacao Res., Trinidad*, 3, 50-62.
———— 1935. The mineral nutrition of plants. The possible application of recent ideas to the growth and manuring of the cacao tree. *Trop. Agriculture, Trin.*, 12, 11-15.
————, and RODRIGUEZ, G. 1935. The effect of manurial treatments on the chemical composition of cacao leaves : the diagnosis of soil and crop nutrient requirements by means of leaf analysis. *Rep. Cacao Res., Trinidad*, 4, 75-82.
MCGEORGE, W. T. 1939. Some problems connected with fertilization of alkali soils. *Calif. Citrogr.*, 24, 389, 424.
MACGILLIVRAY, J. H., RALEIGH, G. J., THUT, H., and VON OHLEN, F. 1930. A study of plant food deficiencies in tomatoes for the canning factory. *Proc. Amer. Soc. hort. Sci.*, 26, 132-136.
MCLARTY, H. R., WILCOX, J. C. and WOODBRIDGE, C. G. 1936. The control of drought spot and corky core of the apple in British Columbia. *Proc. Wash. St. hort. Ass.*, 32, 142-146.
———— ———— ———— 1937. A yellowing of alfalfa due to boron deficiency. *Sci. Agric.*, 17, 515-517.
MCMURTREY, J. E., Jr. 1931. Relation of calcium and magnesium to the growth and quality of tobacco. *J. Amer. Soc. Agron.*, 23, 1051-1052.
———— 1932. Relation of calcium and magnesium to the growth and quality of tobacco. *J. Amer. Soc. Agron.*, 24, 707-716.
MCNAUGHT, K. J. 1938. The cobalt content of North Island pastures. *N. Z. J. Sci. Technol.*, 20, 14A-30A.
MACVICAR, R., TOTTINGHAM, W. E. and RIEMAN, G. H. 1941. The comparative boron content of potato leaves and tubers produced under different cultural conditions. *Amer. Potato J.*, 18, 249-253.
MACY, P. 1936. The quantitative mineral nutrient requirements of plants. *Plant Physiol.*, 11, 749-764.
MAGISTAD, O. C. 1938. A comparison of Mitscherlich trials on Hawaiian soils in Germany and in the Territory of Hawaii. *J. Amer. Soc. Agron.*, 30, 692-698.
MAGNESS, J. R., BATJER, L. P., and REGEIMBAL, L. O. 1940. Correlation of fruit color in apples to nitrogen content of leaves. *Proc. Amer. Soc. hort. Sci.*, 37, 39-42.
MAIER, W. 1943. Eine Bormangelkrankheit des Sellerie (*Apium graveolens* L. var. *rapaceum* (Mill.) DC.). *Gartenbauwiss.*, 18, 47-58.
———— 1944. Bormangel an Weisskohl, Rotkohl, Wirsing, Rosenkohl im Gefässversuch und Freiland. *Gartenbauwiss.*, 18, 288-303.

MANN, C. E. T. and WALLACE, T. 1925. The effects of leaching with cold water on the foliage of the apple. *J. Pomol.*, 4, 146-161. Abridged in *Rep. agric. hort. Res. Sta. Bristol for* 1925, 17-24.

MANSHARD, E. 1933. Untersuchungen über den Nährstoffgehalt der Aschen forstlicher Kulturpflanzen aus den Halstenbecker Forstbaumschulen. *Tharandter forst. Jb.*, 84, 105-158. [quoted by Gast, 1937).

MARSH, A. W. and POWERS, W. L. 1945. Responses of plants to additions of manganese to some Oregon soils. *J. Amer. Soc. Agron.*, 37, 1-8.

MARSH, R. P. 1942. Comparative study of the calcium-boron metabolism of representative dicots and monocots. *Soil Sci.*, 53, 75-78.

——— and SHIVE, J. W. 1941. Boron as a factor in the calcium metabolism of the corn plant. *Soil Sci.*, 51, 141-151.

MARTIN, W. E. 1940. Some effects of cultural practices upon tree composition, yield and quality of Marsh grapefruit in Arizona. *Proc. Amer. Soc. hort. Sci.*, 37, 68-75.

MASCHHAUPT, J. G. 1921. De invloed van grondsoort en bemesting op het gehalte onzer landbouwgewassen aan stikstof en aschbestanddeelen. Vervolg. [German summary.] *Versl. RijkslandbProefst., 's Grav.*, 25, 115-130.

——— 1922. De invloed van grondsoort en bemesting op het gehalte onzer landbouwgewassen aan stikstof en aschbestanddeelen. Vervolg. [German summary.] *Versl. RijkslandbProefst., 's Grav.*, 27, 114-124.

——— 1934. In hoeverre kunnen K, Ca en Mg elkander in de plant vervangen ? *Versl. RijkslandbProefst., 's Grav.*, 40, 1025-1096.

MASON, T. G. and PHILLIS, E. 1943. Studies on the partition of the mineral elements in the cotton plant IV. More about nitrogen, phosphorus, and labile carbohydrate. *Ann. Bot., Lond.* (*N.S.*), 7, 399-408. *Mem. Cott. Res. Sta., Trinidad, Ser. B.*, 16 (1944).

MATHER, T. H. 1929. The effect of fertilizers upon the forms of phosphorus and the amounts of phosphorus, nitrogen, and silica in hays. *Sci. Agric.*, 10, 35-63, 1942.

MAUME, L. 1942. Études biochimiques sur vignes dans les sables du cordon littoral méditerranéen. *Ann. agron.* (*N.S.*), 12, 543-566.

——— 1944. Die Reihenfolge der Notwendigkeit der Anwendung der Nährstoffe beim Weinstock. *Progr. agric. vitic.*, 121, 31-35. [Quoted in *Chem. Zbl.*, 1944 (i), 1216.]

——— and BOUAT, A. 1937. Influences de la variété et du milieu sur l'absorption du soufre par le blé. *C. R. Acad. Agric. Fr.*, 23, 426-430. *Ann. Éc. Agric. Montpellier*, 24, 373-376.

——— and DULAC, J. 1934. Différences variétales, dans l'absorption de l'azote, de l'acide phosphorique et de la potasse par des blés ayant atteint une même époque physiologique dans un même milieu. *C. R. Acad. Sci., Paris*, 198, 199-202.

——— ——— 1934a. Absorption de N, $P_2O_5$, $K_2O$, CaO, MgO par différentes variétés de blé observées la même année dans un même milieu. *Ann. Éc. Agric. Montpellier*, 23, 96-103.

——— ——— 1935. Le rapport C/N dans la plante blé a l'épiaison et a la floraison ; ses notables variations suivant le milieu, *C. R. Acad. Sci., Paris*, 200, 1245-1246. *Ann. Éc. Agric. Montpellier*, 23, 188-190.

——— ——— 1935a. Rôle important du milieu (climat et sol) dans l'absorption de N, $P_2O_5$, $K_2O$, par les blés ayant atteint une même époque physiologique. *C. R. Acad. Agric. Fr.*, 21, 120-123. *Ann. Éc. Agric. Montpellier*, 23, 185-187.

——— ——— 1936. Échantillonage rationnel de la plante blé en vue des analyses chimiques comparatives. *C. R. Acad. Agric. Fr.*, 22, 906-913. 1937. *Ann. Éc. Agric. Montpellier*, 24, 237-242.

——— ——— 1936a. Degré de précision de l'echantillonage de la plante blé à certaines époques physiologiques. *C. R. Acad. Agric. Fr.*, 22, 985-990. 1937. *Ann. Éc. Agric. Montpellier*, 24, 242-248.

——— ——— 1937. Nutrition minérale comparée de blés de printemps et de blés d'automne. *C. R. Acad. Agric. Fr.*, 23, 90-94. *Ann. Éc. Agric. Montpellier*, 24, 369-371.

——— 1938. Comment, à des stades physiologiques définis, se maintient, dans des variétés

et des milieux divers, l'individualité chimique de la tige et de l'épi chez le blé. *C. R. Acad. Sci., Paris*, 206, 1318-1320. 1939. *Ann. Éc. Agric. Montpellier*, 25, 263-266.
———— 1938a. Étude complémentaire au chimisme du blé (nutrition minérale comparée de la tige et de l'épi.) *Ann. Éc. Agric. Montpellier*, 25, 9-13.
———— 1942. Observations sur la physiologie de la nutrition du blé au cours de périodes critiques. Conséquences agronomiques de cette étude pour des blés cultivés dans le midi de la France. *Ann. agron.* (*N.S.*), 12, 193-223.
———— 1945. Une jeune vigne peut tirer parti de certains éléments du sol la même ou une vigne agée souffre de carence prononcée. *C. R. Acad. Agric. Fr.*, 21, 286-289.
———— and Bouat, A. 1934. Dosage rapide et précis de N. P. K, Mg, Ca par semimicroanalyse. *Ann. Éc. Agric. Montpellier*, 23, 5-43.
Maunsell, P. W. 1940. The estimation of boron by means of quinalizarin. *N. Z. J. Sci. Tech.*, 22, 100B—111B.
Mayr, C. and Ahr, —. 1919. Grundlage der Wiesen-düngung nach Ergebnissen von Dauerversuchen in Weihenstephan. Freising, pp. 159. [Quoted by Alway et al., 1926.]
Mehlich, A., Fred, E. B. and Truog, E. 1934. The *Cunninghamella* plaque method of measuring available phosphorus in soil. *Soil. Sci.*, 38, 445-458.
————, Truog, E. and Fred, E. B. 1933. The *Aspergillus niger* method of measuring available potassium in soil. *Soil Sci.*, 35, 259-279.
Menchikowsky, F. and Puffeles, M. 1935. The ratio of Ca, Mg : K, Na and the chlorosis of grapefruit trees in the Jordan Valley. *Hadar*, 8, 161-164.
Merkle, F. G. 1939. Soil testing. Operation, interpretation and application. *Bull. Pa agric. Exp. Sta.* 398, 1-34.
v.d. Merwe, A. D. and Anderssen, F. G. 1937. Chromium and manganese toxicity. Is it important in Transvaal citrus growing ? *Fmg S. Afr.*, 12, 439-440.
Metz, —. 1923. Ueber die wirkung des Natrons neben dem Kali als Nährstoff der Pflanzen. Teil IV : Die Kartoffel. *Ernähr. Pfl.*, 19, 132-136, 140-144, 146-150.
Milad, Y. 1925. The distribution of iron in chlorotic pear trees. *Proc. Amer. Soc. hort. Sci.*, 21, 93-98.
———— 1939. Physiological studies in lime-induced chlorosis. *Bull. Minist. Agric. Egypt* 211, 1-56.
Millikan, C. R. 1944. "Withertop" (calcium deficiency) disease in flax. *J. Dep. Agric. Vict.*, 42, 79-91.
Mitchell, H. L. 1934. Pot culture tests of forest soil fertility with observations on the effect of varied solar radiation and nutrient supply on the growth and nitrogen content of Scots and White Pine seedlings. *Black Rock For. Bull.* 5, i—xii+1-138.
———— 1935. A method for determining the nutrient needs of shade trees with special reference to phosphorus. *Black Rock For. Pap.*, 1, 1-4.
———— 1936. The effect of varied solar radiation upon the growth, development and nutrient content of white pine seedlings grown under nursery conditions. *Black Rock For. Pap.*, 1, 16-22.
———— 1936a. Trends in the nitrogen, phosphorus, potassium and calcium content of the leaves of some forest trees during the growing season. *Black Rock For. Pap.*, 1, 30-44.
———— 1939. The growth and nutrition of white pine (*Pinus Strobus* L.) seedlings in cultures with varying nitrogen, phosphorus, potassium and calcium. With observations on the relation of seed weight to seedling yield. *Black Rock For. Bull.*, 9, i-iv+1-135.
————, and Chandler, R. F., Jr. 1939. The nitrogen nutrition and growth of certain deciduous trees of Northeastern United States. With a discussion of the principles and practice of leaf analysis as applied to forest trees. *Black Rock For. Bull.* 11, i-viii+1-94.
———— and Finn, R. F. 1935. The relative feeding power of oaks and maples for soil phosphorus. *Black Rock For. Pap.*, 1, 6-9.
Mitscherlich, E. A. 1909. Das Gesetz des Minimums und das Gesetz des abnehmenden Bodenertrages. *Landw. Jb.*, 38, 537-552
———— 1919. Zum Gehalt der Haferpflanze an Phosphorsäure und seinen Beziehungen zu der durch eine Nährstoffzufuhr bedingten Ertragserhöhung. *J. Landw.*, 67, 171-176.

MITSCHERLICH, E. A. 1925. Die Bestimmung des Düngerbedürfnisses des Bodens. 2te Auflage. Verlagsbuchlandlung Paul Parey, Berlin, pp. 103.
MOIR, W. W. G. 1935. A fertilizer policy developed with the aid of experiments. *Hawaii Plant. Rec.*, 39, 113-136.
MORGAN, M. F. 1930. The soils of Connecticut. Progress report of investigations 1924-1930 *Bull. Conn. agric. Exp. Sta.* 320, 825-911.
——— 1933. Choix de méthodes uniformes et appropriées pour la détermination des besoins d'engrais des terrains. [German summary]. *Conf. intern. Engr. chim.*, 2, 167-177.
——— 1935. The Universal soil testing system. *Bull. Conn. agric. Exp. Sta.* 372; revised 1937 as *Bull.* 392, 127-159.
——— 1937. Soil and plant tissue tests for minor element constituents. *Proc. Soil. Sci. Soc. Amer.*, 1, 255-257.
——— 1939. Soil testing methods. The Universal soil testing system. *Circ. Conn. agric. Exp. Sta.* 127, 1-16.
MORRIS, A. A. 1937. The effect of differential fertilizer treatments on the yield and quality of fruit from mature bearing Valencia Late trees on Mazoe Citrus Estate, Southern Rhodesia. *Rep. Mazoe Citrus exp. Sta. for* 1936, 107-153.
——— 1938. Some observations on the effects of boron treatment in the control of " hard fruit " in citrus. *J. Pomol.*, 16, 167-181.
MOSER, F. 1941. Plant composition as an index of soil fertility. *Proc. Soil. Sci. Soc. Amer.*, 5, 147-151.
——— 1941a. Plant's contents show its nutrient needs. *Better Crops with Plant Food*, 25 (6), 9-11, 39-40.
MUCKENHIRN, R. J. 1936. Response of plants to boron, copper, and manganese. *J. Amer. Soc. Agron.*, 28, 824-842.
MUHR, G. R. 1941. Available boron as affected by soil treatments. *Proc. Soil Sci. Soc. Amer.*, 5. 220-226.
——— 1942. Plant symptoms of boron deficiency and the effects of borax on the yield and chemical composition of several crops. *Soil Sci.*, 54, 55-65.
MULDER, E. G. 1938. *Ann. Ferment.*, 4, 513-533. [quoted by Acock (1941)].
MÜLLER, F. 1915. Das Düngerbedürfnis des Bodens. *Landw. Jb. Schweiz*, 29, 119-134.
MÜNTER, F. 1919. Pflanzenanalyse und Düngerbedürfnis des Bodens. *J. Landw.*, 67, 229-266.
——— 1920. Pflanzenanalyse und Düngung. *J. Landw.*, 68, 207-224.
——— 1920a. Die Zuckerrübe als Bodenanalysatorin. *Mitt. dtsch. LandwGes.* 35, 313-314.
NANNINGA, A. W. 1903. Invloed van den bodem op de samenstelling van het theeblad en de qualiteit der thee. Deel I. *Meded. PlTuin, Batavia* 65, 1-49.
—— —— 1904. Invloed van den bodem op de samenstelling van het theeblad en de qualiteit der thee. Deel II. *Meded. PlTuin, Batavia* 72, 1-56.
NASHARTY, A. H. 1944. Accumulation of nitrogen from different sources by peach trees. *Proc. Amer. Soc. hort. Sci.*, 45, 5-8.
NEEB, G. A. 1931. De Hoffer'sche ijzerreactie bij suikerriet in verband met het kali-vraagstuk. *Arch, Suikerind, Ned.-Ind.*, 39, 813-834.
NELLER, J. R. 1935. Phosphorus content and buffer capacity of plant sap as related to the physiological effect of phosphorus fertilizers in fibrous low-moor peat. *J. agric. Res.*, 51, 287-300.
NÉMEC, A. 1938. Über den Einfluss des Kalkens auf das Wachstum und auf die Ernährung der Fichte in Waldbaumschulen. *Bodenk. PflErnähr.*, 7, 77-99.
—— —— 1939. Untersuchungen über den Einfluss chlorhaltigen Kalidüngemittel auf das Wachstum und auf die Ernährung der Fichte in Waldbaumschulen. *Bodenk. PflErnähr.*, 13, 35-72.
—— —— 1942. Zur Kenntnis der Kali- und Magnesiamangelerscheinungen bei Sämlingen und Kulturen der Kiefer. *Forstwiss, Zbl.*, 64, 160-166.
NEUBAUER, H. 1923. Ein Laboratoriumsverfahren zur Bestimmung der von den Pflanzen aus dem Boden aufnehmbaren Mengen von Phosphorsäure und Kali. *Landw. VersSta.*, 100, 119-128.

———, Bonewitz, W. and Schottmüller, A. 1928. Vergleiche zwischen Bodenuntersuchungen nach der Keimpflanzenmethode und nach der Methode von Mitscherlich. *Landw. VersSta.*, 107, 131-142.
——— and Schneider, W. 1923. Die Nährstoffaufnahme der Keimpflanzen und ihre Anwendung auf die Bestimmung des Nährstoffgehalts der Böden. *Z. PflErnähr. Düng. A.*, 2, 329-362.
New Jersey Agricultural Experiment Station. 1939. The relation of the pH value of the culture solution to the availability of boron for the growth of radish plants. *Rep. N. J. agric. Exp. Sta. for* 1938-9, 60, 104-105.
New Zealand Department of Scientific and Industrial Research. 1937. Fruit research. Physiological diseases. *Rep. Dep. sci. industr. Res. N. Z.*, 11, 55-56.
——— ——— ——— ——— ——— 1942. Fruit research. Apple. (b) "Minor" element studies. *Rep. Dep. sci. industr. Res. N. Z.*, 16, 16-17.
Nicholas, D. J. D. 1945. The mineral element content of flax straw from experimental centres. Season 1943. *Rep. agric. hort. Res. Sta. Bristol for* 1944, 98-110.
——— and Jones, J. O. 1945. The application of rapid chemical tests to plant tissues in the diagnosis of deficiencies of mineral nutrients. Progress report I. *Rep. agric. hort. Sta. Bristol for* 1944, 84-97.
Nicol, H. 1939. Bacteria as indicators of soil fertility. *Chron. Bot.*, 5, 13-14.
Nightingale, G. T. 1937. Potassium and calcium in relation to nitrogen metabolism. *Bot. Gaz.*, 98, 725-734.
——— 1942. Nitrate and carbohydrate reserves in relation to nitrogen nutrition of pineapple. *Bot. Gaz.*, 103, 409-456.
——— 1942a. Potassium and phosphate nutrition of pineapple in relation to nitrate and carbohydrate reserves. *Bot. Gaz.*, 104, 191-223.
———, Addoms, R. M., Robbins, W. R. and Schermerhorn, L. G. 1931. Effects of calcium deficiency on nitrate absorption and on metabolism in tomato. *Plant Physiol.*, 6, 605-630.
Niklas, H. and Hirschberger, W. 1924. Eine neue Methode zur raschen Ermittlung der Phosphorsäurebedürftigkeit unserer Böden. *Z. angew. Chem.*, 37, 955-957.
———, Poschenrieder, H. and Trischler, J. 1930. Eine neue mikrobiologische Methode zur Feststellung der Düngebedürftigkeit der Böden. 1, Mitteilung: Bestimmung der Kalidüngebedürftigkeit der Böden mittels *Aspergillus niger*. *Z. PflErnähr. Düng. A.*, 18, 129-157.
——— ——— ——— 1930a. Die Kultur des Schimmelpilzes *Aspergillus niger* zur biochemischen Bestimmung der Kali- u. Phosphorsäuredüngebedürftigkeit der Böden. *Ernähr. Pfl.*, 26, 97-103.
Nishimura, T. and Hance, F. E. 1938. The analysis of plant material for total nitrogen, phosphate and potash—an improved and simplified R.C.M. procedure. *Hawaii. Plant Rec.*, 42, 119-123.
Nolte, O. 1927. Die Bedeutung des Kalis und der in den Kalirohsalzen enthaltenden Nebensalze für den Böden und die der menschlichen Ernährung unmittelbar dienenden Pflanzen. *Landw. VersSta.*, 106, 1-123.
Ohlrogge, A. J. 1941. Plant tissue test as a diagnostic aid in fertilizer placement studies. *Proc. nat. Jt Comm. Fert. Appl.*, 17, 39.
——— 1941a. Plant tissue test as an aid in fertilizer studies. *Proc. nat. Jt Comm. Fert. Appl.*, 17, 40.
Olsen, C. 1935. Iron absorption and chlorosis in green plants. *C. R. Lab. Carlsberg, Ser. chim.*, 21, 15-52.
——— 1938. Experiments with different quantities of iron salts given to maize in water culture. *C. R. Lab. Carlsberg., Ser. chim.*, 21, 301-313.
Olson, L. C. 1942. Laboratory data as an aid in interpreting the results of cotton and corn fertilizer experiments in Georgia. *Proc. Soil. Sci. Soc. Amer.*, 6, 238-242.
——— 1942a. Results of plant tissue tests and soil tests for predicting the fertilizer requirements of cotton and corn. *Proc. Assoc. south. agric. Workers*, 43, 78.

Olson, O. E., Jornlin, D. F., and Moxon, A. L. 1942. The selenium content of vegetation and the mapping of seleniferous soils. *J. Amer. Soc. Agron.*, 34, 607-615.
——— ——— ——— 1942a. Field studies on methods for determining availability of selenium to plants. *Soil Sci.*, 53, 365-368.
Opitz, K. 1944. Über das Aneignungsvermögen und das Düngebedürfnis einiger Kulturpflanzen für Phosphorsäure. *Bodenk. PflErnähr.*, 35, 58-71.
Oserkowsky, J. 1932. Hydrogen-ion concentration and iron content of tracheal sap from green and chlorotic pear trees. *Plant Physiol.*, 7, 253-259.
——— 1933. Quantitative relation between chlorophyll and iron in green and chlorotic pear leaves. *Plant Physiol.*, 8, 449-468.
——— and Thomas, H. E. 1933. Exanthema in pears and its relation to copper deficiency. *Science* (*N.S.*), 78, 315-316.
——— ——— 1938. Exanthema in pear, and copper deficiency. *Plant Physiol.*, 13, 451-467.
Otto, R. and Kooper, W. D. 1910. Beiträge zur Abnahme bezw. Rückwanderung der Stickstoffverbindungen aus den Blättern während der Nacht, sowie zur herbstlichen Rückwanderung von Stickstoffverbindungen aus den Blättern. *Landw. Jb.*, 39, 167-172.
Page, N. R. and Burkhart, L. 1941. Extraction and distribution of soluble minerals in the peanut plant. *Proc. Assoc. south. agric. Workers*, 42, 210-211.
Painter, J. H. and Drosdoff, M. 1943. Results of preliminary tests on correction of potassium deficiency in tung. *Proc. Amer. Soc. hort. Sci.*, 42, 65-68.
Parbery, N. H. 1935. Mineral constituents in relation to chlorosis of orange leaves. *Soil Sci.*, 39, 35-45.
——— 1937. Magnesium deficiency in cabbages and cauliflowers. *Agric. Gaz. N. S. W.*, 48, 556-558, 577.
——— 1941. Bean diseases common in Wyong district. *Banana Bull.*, 1 (60), 9.
——— 1943. The excessive uptake of manganese by beans showing scald and magnesium deficiency. Its regulation by liming. *Agric. Gaz. N. S. W.*, 54, 14-17.
Parks, R. Q., Hood, S. L., Hurwitz, C. and Ellis, G. H. 1943. Quantitative chemical microdetermination, of twelve elements in plant tissue. *Industr. Engng Chem., Anal. Ed.* 15, 327-333.
Parsche, F. 1936. Über die Kalkchlorose der Lupinen. *Z. PflErnähr. Düng.*, 41, 282-312.
Peech, M. and English, L. 1944. Rapid microchemical soil tests. *Soil. Sci.*, 57, 167-195.
Penston, N. L. 1935. Studies of the physiological importance of the mineral elements in plants VIII. The variation in potassium content of potato leaves during the day. *New Phytol.*, 34, 296-309.
——— 1938. Studies of the physiological importance of the mineral elements in plants. The variation in potassium content of maize leaves during the day. *New Phytol.*, 37, 1-14.
Petersen, P. 1876. Ueber das Minimum der für die Haferpflanze nöthigen Phosphorsäure und über die nutzbare Verbindungsform der Phosphorsäure. *Wochenschr. Pommerschen ökon. Ges.*, 3. [quoted in *Jber. Fortschr. Agrik Chem.* 18/19 (1875/6), 251-252.]
Peterson, W. H. 1914. Forms of sulfur in plant materials and their variation with the soil supply. *J. Amer. chem. Soc.*, 36, 1290-1300.
Petrie, A. H. K. 1937. Physiological ontogeny in plants and its relation to nutrition. 3. The effect of nitrogen supply on the drifting composition of the leaves. *Aust. J. exp. Biol. med. Sci.*, 15, 385-404.
Pettinger, N. A. 1931. The expressed sap of corn plants as an indicator of nutrient needs. *J. agric. Res.*, 43, 95-119.
——— 1932. Effect of fertilizers on the chlorine content of the sap of corn plants. *J. agric. Res.*, 44, 919-931.
——— and Thornton, S. F. 1934. A comparison of the Neubauer, plant-sap analysis, and Hoffer stalk-test methods for determining the nutrient supply of soils. *J. Amer. Soc. Agron.*, 26, 547-561.
Pfeiffer, T., Blanck, E., and Flügel, M. 1912. Wasser und Licht als Vegetationsfaktoren und ihre Beziehungen zum Gesetze vom Minimum. *Landw. VersSta.*, 76, 169-236.

——— ——— and Friske, K. 1913. Der Einfluss verschiedener Vegetationsfaktoren, namentlich des Wassers, auf die Erzielung von Maximalerträgen in Vegetationsgefässen. *Landw. VersSta.*, 82, 237-298

——— ———, Simmermacher, W., and Rathmann, W. 1915. Pflanzenanalyse und Bodenanalyse zur Bestimmung des Nährstoffgehaltes der Ackerböden. *Landw. VersSta.*, 86, 339-391.

———, Simmermacher, W. and Rippel, A. 1919. Der Gehalt der Haferpflanzen an Stickstoff, Phosphorsäure und Kali unter verschiedenen Bedingungen und seine Beziehungen zu der durch eine Nährstoffzufuhr bedingten Ertragserhöhung. *J. Landw.*, 67, 1-57.

Pfützer, G., and Roth, H. 1942. Der Phosphatid-Gehalt von Pflanzen in Abhängigkeit von ihrer Mineralstoffernährung. *Chemie*, 55, 289-293.

Phillis, E., and Mason, T. G. 1937. Concentration of solutes in vacuolar and cytoplasmic sap. *Nature, Lond.*, 140, 370-372.

——— ——— 1939. Studies on the partition of the mineral elements in the cotton plant I. Preliminary observations on nitrogen and phosphorus. *Ann. Bot., Lond.* (*N.S.*), 3, 569-585. *Mem. Cott. Res. Sta., Trinidad, Ser. B.*, 11.

Phillis, E., and Mason, T. G. 1940. Studies on the partition of the mineral elements in the cotton plant II. Preliminary observations on potassium, calcium and magnesium. *Ann. Bot., Lond.* (*N.S.*), 4, 773-789. *Mem. Cott. Res. Sta., Trinidad Ser. B.*, 14 (1941).

——— ——— 1942. On diurnal variations in the mineral content of the leaf in the cotton plant. *Ann. Bot., Lond.* (*N,S,*), 6, 437-442. *Mem. Cott. Res. Sta. Trinidad, Ser. B.*, 15 (1943).

Pierre, W. H., and Pohlman, G. G. 1933. Preliminary studies of the exuded plant sap and the relation between the composition of the sap and the soil solution. *J. Amer. Soc. Agron.*, 25, 144-160.

Pigorini, L. 1914. Studi sulla foglia di gelso : sulla composizione chimica della foglia al mattino e alla sera. *R. C. Accad. Lincei, Ser.* 5, 23 (ii), 433-437.

Piper, C. S. 1931. The availability of manganese in the soil. *J. agric. Sci.*, 21, 762-779.

——— 1936. The boron status of South Australian apples. *J. Coun. sci. industr. Res. Aust.*, 9, 245-248.

——— 1940. The symptoms and diagnosis of minor-element deficiencies in agricultural and horticultural crops. Pt. I. Diagnostic methods. Boron. Manganese. *Emp. J. exp. Agric.*, 8, 85-96.

——— 1942. Investigations on copper deficiency in plants. *J. agric. Sci.*, 32, 143-178.

——— 1942a. Soil and plant analysis. A laboratory manual of methods for the examination of soils and the determination of the inorganic constituents of plants. A monograph from the Waite Agricultural Research Institute. The University of Adelaide, Adelaide, pp. xiv × 368.

——— and Walkley, A. 1943. Copper, zinc, and manganese in some plants of agricultural interest. *J. Coun. sci. industr. Res. Aust.* 16, 217-234.

Plant, W. 1945. The incidence of potash deficiency in the Ormskirk area. Agric. Res. Coun. Unpublished report duplicated for private circulation. A.R.C. 7823, pp. 6.

——— 1945a. Nutritional survey of crops in the West Riding of Yorkshire. Agric. Res. Coun. Unpublished report, duplicated for private circulation. A.R.C. 7826, pp. 6.

——— 1945b. A nutritional survey of crops in Cumberland. Agric. Res. Coun. Unpublished report, duplicated for private circulation. A.R.C. 7827, pp. 8.

———, Jones, J. O., and Nicholas, D. J. D. 1945. The technique of chemical tissue tests. Progress report I. *Rep. agric. hort. Res. Sta. Bristol for* 1944, 79-84.

Poehlman, J. M. 1935. Some limitations of plant juice analyses as indicators of the nutrient needs of plants. *J. Amer. Soc. Agron.*, 27, 195-207.

Pohlman, G. G., and Pierre, W. H. 1933. The phosphorus concentration of the exuded sap of corn as a measure of the available phosphorus in the soil. *J. Amer. Soc. Agron.*, 25, 160-171.

Potter, G. F., and Percival, G. P. 1938. Availability to apple trees of potassium applied on the surface of sod mulch orchards in New Hampshire. *Proc. Amer. Soc. hort. Sci.*, 35, 335-338.

Purvis, E. R., and Blume, J. M. 1941. Rapid soil tests for determining the fertilizer requirements of vegetable crops in Eastern Virginia. *Bull. Va Truck Exp. Sta.* 106, 1745-1756.
Quiñones, P. E. 1940. Preliminary study of the mottling of pineapple leaves. *Bol. Assoc. quim. P.R.*, 1 (4), 15-16. [Quoted in *Chem. Abs.*, 37, 6079.]
Rademacher, B. 1935. Die Heidemoorkrankheit (Urbarmachungskrankheit) unter besonderer Berücksichtigung der Kupferfrage. *Arb. biol. Reichsanst,. Berl.*, 21, 531-603.
———— 1937. Kupfergehalt, Kupferbedarf und Kupferaneignungsvermögen verschiedener Hafersorten als Grundlage für die Züchtung gegen die Heidemoorkrankheit widerstandsfähiger Sorten. *Z. PflKrankh.*, 47, 545-560.
Raleigh, S. M., and Chucka, J. A. 1944. Effect of nutrient ratio and concentration on growth and composition of tomato plants and on the occurrence of blossom-end rot of the fruit. *Plant Physiol.*, 19, 671-678.
Raum, H. 1926. Grundsätze der Wiesendüngung. *Z. PflErnähr. Düng. B.*, 5, 193-207.
Ravaz, —., Lagatu, —., and Maume, —. 1928. Un cas spécial de chlorose des vignes américaines greffées. *Ann. Éc. Agric. Montpellier*, 19, 159-179.
Ravikovitch, S., and Bidner, N. 1937. The deterioration of grapevines in saline soils. *Emp. J. exp. Agric.*, 5, 197-203.
Reed, H. S., and Haas, A. R. C. 1923. Effect of sodium chlorid and calcium chlorid upon growth and composition of young orange trees. *Tech. Pap. Calif. agric. Exp. Sta.* 4, 1-32.
Reeve, E., Prince, A. L., and Bear, F. E. 1944. The boron needs of New Jersey soils. *Bull. N.J. agric. Exp. Sta.* 1, 709, 1-26.
———— and Shive, J. W., 1943. Potassium-boron relations in plants. *Better Crops with Plant Food*, 27 (4), 14-16, 45-48.
Remington, R. E., Culp, F. B., and von Kolnitz, H. 1929. The potato as an index of iodine distribution. *J. Amer. chem. Soc.*, 51, 2942-2947.
Remy, T. 1903. Die wichtigsten Ergebnisse der im Jahre 1902 durchgeführten Versuche auf dem Gebiete des Gersten- und Hopfenbaues. *Jb. VersAnst. Brau. Berl.*, 5, 72-76.
———— 1903a. Ziele und Ergebnisse der letztjährigen Versuchsthätigkeit auf dem Gebiete des Gersten- und Hopfenbaues. III. Düngungsversuche zu Hopfen. 2. Einige Bemerkungen über die Feststellung des Düngerbedürfnisses der Hopfenböden. *Jb. VersAnst. Brau. Berl.*, 5, 230-232.
———— 1903b. Die Blattanalyse als Hilfsmittel zur Feststellung des Düngerbedürfnisses der Hopfenböden. *Jb. VersAnst. Brau. Berl.*, 6, 83-85.
———— 1906. Die Bedeutung der Pflanzenanalyse für die Feststellung des Düngerbedürfnisses der Böden. *Ber. Inst. Bodenlehre PflBau Poppelsdorf*, 1905-1906. [Quoted in *Jber. AgrikChem.* 3 *Folge*, 10, 175.]
———— 1906a. Düngerbedürfnis der Obstgärten. *Ber. Inst. Bodenlehre PflBau Poppelsdorf*, 1905-1906. [Quoted in *Jber. AgrikChem.* 3 *Folge*, 10, 191.]
Remy, T. 1911. Zur Düngung der Wiesen. *Mitt. dtsch. LandwGes.*, 26, 615-619.
Reuther, W. 1941. Effect of certain orchard practices on the potassium status of a New York fruit soil. *Soil Sci.*, 52, 155-165.
———— 1941a. Studies concerning the supply of available potassium in certain New York orchard soils. *Mem. Cornell agric. Exp. Sta.* 241, 1-51.
———— and Boynton, D. 1940. Variations in potassium content of the foliage from certain New York orchards. *Proc. Amer. Soc. hort. Sci.*, 37, 32-38.
Rhode Island Agricultural Experiment Station. 1933. Soil nitrate levels and certain fractions of nitrogen in plant juices. *Rep. R. I. agric. Exp. Sta.*, 45, 49-50.
———— 1934. Certain components of the juice of celery as an index to current supplies of nitrogen. *Rep. R.I. agric. Exp. Sta.*, 46, 68-69.
———— 1935. Measurements of nitrate nitrogen as indices of current nitrogen supplies. *Rep. R.I. agric. Exp. Sta.*, 47, 69-71.
Richards, F. J. 1932. Physiological studies in plant nutrition. III. Further studies of the effect of potash deficiency on the rate of respiration in leaves of barley. *Ann. Bot., Lond.*, 46, 367-388.
———— 1944. Mineral nutrition of plants. *Ann. Rev. Biochem.*, 13, 611-630.

———— and Templeman, W. G. 1936. Physiological studies in plant nutrition IV. Nitrogen metabolism in relation to nitrogen deficiency and age of leaves in barley. *Ann. Bot., Lond.*, 50, 367-402.
Riches, J. P. 1945. Notes on the possibilities of analysing plant tissue by means of the polarograph. Agric. Res. Coun. Unpublished report duplicated for private circulation. A.R.C. 7849, 25-31.
Rigg, T., Askew, H. O., and Chittenden, E. 1937. Brown-heart of swedes and turnips in Nelson district : a boron deficiency ailment. *N.Z.J. Sci. Tech.*, 18, 750-755.
(Roach, W. A.) 1930. Biochemistry. Stock influence. *Rep. E. Malling Res. Sta. for* 1929 (A 12), 63.
Roach, W. A. 1931. The chemistry of the rootstock-scion effect. I. The elements absorbed from the soil. A progress report. *Rep. E. Malling Res. Sta. Supplement for* 1928-30 (A14). 101-104.
———— 1933. Distribution of molybdenum. *Nature, Lond.*, 131, 202.
———— 1938. Plant injection for diagnostic and curative purposes. *Tech. Commun. Bur. Hort. E. Malling* 10, 1-78.
———— 1939. Plant injection as a physiological method. *Ann. Bot., Lond.* (*N.S.*), 3, 155-226.
———— 1939a. Flame method of spectrochemical analysis. *Nature, Lond.*, 144, 1047.
———— 1940. Diagnosis of mineral deficiencies and excesses by systematic leaf injection and analysis. *Rep. E. Malling Res. Sta. for* 1939 (A23), 51-58.
———— 1943. The diagnosis of mineral deficiency by plant analysis and plant injection. *Occas. Publ. sci. Hort.*, 4, 40-41.
———— 1944. The present position regarding the diagnosis of mineral deficiencies in fruit trees by plant analysis and plant injection. *Rep. E. Malling Res. Sta. for* 1943 (A27), 99-103.
———— 1945. Mineral deficiencies in agricultural and horticultural crops. *Rep. E. Malling Res. Sta. for* 1944 (A28), 43-60.
———— and Bolas, B. D. 1943. General review of research work with lists of papers published during the year. IV. Biochemistry. *Rep. E. Malling Res. Sta. for* 1942 (A26), 21-22.
———— ———— 1944. General review of research work with lists of papers published during the year. IV. Biochemistry. *Rep. E. Malling Res. Sta. for* 1943 (A27), 22-23.
————, Majewski, F., and Thompson, S. G. 1939. Biochemistry. Elementary analysis. (ii) Spectrographic. *Rep. E. Malling Res. Sta. for* 1938 (A22), 72.
———— and Roberts, W. O. 1945. Further work on plant injection for diagnostic and curative purposes. *J. Pomol.*, 21, 108-119. *Tech. Commun. Bur. Hort. E. Malling* 16, 1-12.
Roberts, W. O. 1945. Combined mineral deficiencies in fruit trees. *Rep. E. Malling Res. Sta. for* 1944 (A28), 64-67.
———— 1945a. Leaf painting as a method of diagnosis of mineral deficiency. *Rep. E. Malling Res. Sta. for* 1944 (A28), 67-68.
Robinson, W. O. 1943. The occurrence of rare earths in plants and soils. *Soil Sci.*, 56, 1-6.
———— and Edgington, G. 1942. Boron content of hickory and some other trees. *Soil Sci.*, 53, 309-312.
Roy, W. R. 1943. Studies of boron deficiency in grapefruit. *Citrus Ind.*, 24 (8), 4-5 and (9), 5, 8. [Quoted in Chem. Abs., 37, 6306.)
Sabinin, D. A. 1928. Principles and methods of study of the mineral composition of exuded sap. [Russian, with German summary.] *Mitt. Abt. Ackerbau st. Inst. exp. Agron.* 15, 1-48.
————, Minina, E. G., and Trubeckova, O. M. 1929. The study of exuded sap as a method of investigating mineral uptake. Russian, with German summary. *Mitt. Abt. Ackerbau st. Inst. exp. Agron.* 16, 1-44.
Salter, R. M., and Ames, J. W. 1928. Plant composition as a guide to the availability of soil nutrients. J. Amer. Soc. Agron., 20, 808-836.

SAMUEL, G., and PIPER, C. S. 1928. Grey speck (manganese deficiency) disease of oats. *J. Dep. Agric. S. Aust.*, 31, 696-700, 702, 704, 705, 789-799.
———— ———— 1929. Manganese as an essential element for plant growth. *Ann. appl. Biol.*, 16, 493-524.
SANDROCK, W. 1931. Kritische Betrachtungen zur Blattdiagnose nach Lagatu bei der Kartoffel unter besonderer Berücksichtigung des im Boden durch die Keimpflanzenmethode ermittelbaren wurzellöslichen Nährstoffvorrates. *Z. PflErnähr. B.*, 10, 188-201.
SARTORY, A., SARTORY, R., MEYER, J., and ARNOLD, F. 1935. Étude préliminaire en milieux synthétiques définis des facteurs culturaux nécessaires pour déterminer la fertilité du sol au moyen du *Sterigmatocystis nigra* Cramer. *C.R. Acad. Sci., Paris*, 200, 1692-1694.
SAYRE, C. B. 1941. Plant tissue tests may be valuable aid to farmers. *Fm Res.*, 7 (1), 11, 14. [Quoted in *Exp. Sta. Rec.*, 84, 590.]
SCARSETH, G. D. 1941. Soil and plant-tissue tests as aids in determining fertilizer needs. *Better Crops with Plant Food*, 25 (3), 9-11, 43-47.
———— 1941a. Soil and plant tissue tests as diagnostic aids in determining fertilizer needs. *Proc. Assoc. south. agric. Workers*, 42, 53-54.
———— 1941b. The use of plant tissue tests in fertility research in Indiana. *Proc. nat. Jt Comm. Fert. Appl.*, 17, 35-36.
———— 1942. Tissue testing (quick test) in diagnosis. *Amer. Fertil.*, 97 (7), 22.
———— 1943. Methods of diagnosing plant nutrient needs. *Amer. Fertil.*, 98 (12), 5-8. 22, 24, 26.
———— 1943a. Plant-tissue testing in diagnosis of the nutritional status of growing plants, *Soil Sci.*, 55, 113-120.
———— 1943b. Double-quick fertility. *Country Gentleman* (May).
————, COOK, H. L., KRANTZ, B. A., and OHLROGGE, A. J. 1943. How to fertilize corn effectively in Indiana. *Bull. Ind. agric. Exp. Sta.* 482, 1-39.
SCHNEIDER, P. 1905. Die Pflanzenanalyse als Hilfsmittel zur Bestimmung des Nährstoffbedürfnisses unter besonderer Berücksichtigung des Hopfens. *Wschr. Brau,*. 22, 456-458.
SCHOLZ, W. 1933. Die Chlorose der gelben Lupine (*Lupinus luteus*) in ihrer Beziehung zum Eisen. *Z. PflErnähr. Düng. A*, 28, 257-298.
VAN SCHREVEN, D. A. 1937. Een onderzoek naar de beteekenis van natrium voor den groei en de ionenopname van de suikerbiet. I. Proeven in water-, zand- en grondcultures met NaCl. *Meded. Inst. Suikerbiet., Bergen-o.-Z.*, 7, 119-226.
———— 1938. Een onderzoek naar den invloed van het water op den groei en de samenstelling van de suikerbiet. II. Onderzoek naar de uitscheiding van elementen door het blad. *Meded. Inst. Suikerbiet., Bergen-o.-Z.*, 8, 89-135.
SCHULZE, B., and SCHÜTZ, J. 1909. Die Stoffwandlungen in den Laubblättern des Baumes insbesondere in ihren Beziehungen zum herbstlichen Blattfall. *Landw. VersSta.*, 71, 299-352.
SCHUSTER, C. E., and STEPHENSON, R. E. 1940. Sunflower as an indicator plant of boron deficiency in soils. *J. Amer. Soc. Agron.*, 32, 607-621.
SCOFIELD, C. S., and WILCOX, L. V. 1931. Boron in irrigation waters. *Tech. Bull. U.S. Dep. Agric.* 264, 1-65.
———— ————, and BLAIR, G. Y. 1940. Boron absorption by sunflower seedlings. *J. agric. Res.*, 61, 41-56.
SCOTT, L. E. 1941. An instance of boron deficiency in the grape under field conditions. *Proc. Amer. Soc. hort. Sci.*, 38, 375-378.
———— 1944. Boron nutrition of the grape. *Soil Sci.*, 57, 55-65.
SCURTI, F. 1940. Il controllo della fertilità nella coltivazione dei terreni agrari. *Ital. agric.*, 77, 151-159.
SEIDEL, K. 1931. Eine neue mikrobiologische Methode zur Beurteilung der Nährstoffverhältnisse eines Bodens. *Arch. PflBau.*, 6, 536-576.
SEKERA, F., and SCHOBER, K. 1934. Der Mikro-Düngungsversuch zur Bestimmung der Düngerwirkung von Phosphorsäure und Kali. *Phosphorsäure*, 4, 321-351.
SEN, A. T. 1938. Annual report of the agricultural chemist, Burma, for the year ending the

31st March, 1938. II. Research. (d) The spectrographic examination of *Myitpo* affected paddy plants. *Rep. Dep. Agric. Burma for* 1937-8, 35.

———— 1938a. Annual report of the agricultural chemist, Burma, for the year ending the 31st March, 1938. II. Research. (e) Further experiments on the occurrence of depressed yellow patch of paddy in the Mandalay Farm. *Rep. Dep. Agric. Burma for* 1937-8, 35-36.

SHAW, J. K. 1935. Some experiences with the Thornton test for potash in apple trees. *Proc. Amer. Soc. hort. Sci.*, 32, 56-60.

SHEAR, G. M., and USSERY, H. D. 1940. Frenching of tobacco distinguished from thallium toxicity by spectrographic analysis. *J. agric. Res.*, 60, 129-139.

SHEDD, O. N. 1917. Effect of sulphur on different crops and soils. *J. agric. Res.*, 11, 91-103.

SIMAKOVA, T., and BOVSCHIK, G. 1932. Ueber die mikrobiologische Methode zur Bestimmung des Phosphorbedürfnisses des Bodens mittels *Aspergillus niger*. *Z. PflErnähr. Düng. A*, 24, 341-353.

SJOLLEMA, B. 1933. Kupfermangel als Ursache von Krankheiten bei Pflanzen und Tieren. *Biochem. Z.*, 267, 151-156.

SKINNER, W. W. (Chairman, Editorial Board). 1935. Official and tentative methods of analysis of the Association of Official Agricultural Chemists. 4th Edition. A.O.A.C., Washington, D.C. pp. xx + 710.

SMITH, M. E. 1944. The role of boron in plant metabolism. 1. Boron in relation to the absorption and solubility of calcium. *Aust. J. exp. Biol. med. Sci.*, 22, 257-263.

SMITH, O., and NASH, L. B. 1937. Soil reaction, available nutrients and composition of the potato plant. *Proc. Amer. Soc. hort. Sci.*, 34, 445-448.

SMOCK, R. M., and BOYNTON, D. 1944. The effects of differential nitrogen treatments in the orchard on the keeping quality of McIntosh apples. *Proc. Amer. Soc. hort. Sci.*, 45, 77-86.

SNELL, J. F., and MCKIBBIN, R. R. 1933 Choix de méthodes uniformes et appropriées pour la détermination des besoins d'engrais des terrains. [French and German.] *Conf. intern. Engr. chim.*, 2, 143-152.

SOMERS, I. I., and SHIVE, J. W. 1942. The iron-manganese relation in plant metabolism. *Plant Physiol.*, 17, 582-602.

SOULMAGNON, M. 1933. Choix de méthodes uniformes et appropriées pour la détermination des besoins d'engrais des terrains. [French and German.] *Conf. intern. Engr. chim.*, 2, 240-246.

SOUTHWICK, L. 1943. Magnesium deficiency in Massachusetts apple orchards. *Proc. Amer. Soc. hort. Sci.*, 42, 85-94.

———— and SHAW, J. K. 1944. Some results in correcting magnesium deficiency in apple orchards. *Proc. Amer. Soc. hort. Sci.*, 44, 8-14.

———— and SMITH, C. T. 1945. Further data on correcting magnesium deficiency in apple orchards. *Proc. Amer. Soc. hort. Sci.*, 46, 6-12.

SPENCER, E. L., and LAVIN, G. I. 1939. Frenching of tobacco. *Phytopath.*, 29, 502-503.

SPURWAY, C. H. 1938. Soil testing. A practical system of soil diagnosis. *Tech. Bull. Mich. agric. Exp. Sta.* 132, 1-16.

———— 1940. Electro-foliar diagnosis. *Science* (*N.S.*), 92, 489-490.

STAHL-SCHRÖDER, M. 1904. Kann die Pflanzenanalyse uns Aufschluss über den Gehalt an assimilierbaren Nährstoffen im Boden geben ? *J. Landw.*, 52, 31-92, 193-268.

STANFORD, G., KELLY, J. B., and PIERRE, W. H. 1942. Cation balance in corn grown on high-lime soils in relation to potassium deficiency. *Proc. Soil Sci. Soc. Amer.*, 6, 335-341.

STECKEL, J. E. 1941. Plant tissue test case of lawn sodded on Miami subsoil, Lafayette, Indiana. *Proc. nat. Jt. Comm. Fert. Appl.*, 17, 44.

STEPHENS, C. G., and OERTEL, A. C. 1943. Responses of plants to molybdenum in pot experiments on the Cressy Shaley clay-loam. *J. Coun. sci. industr. Res. Aust.*, 16, 69-73.

STEWART, L. C., SACKETT, W. G., ROBERTSON, D. W., and KEZER, A. 1932. A comparison of the soil-plaque method with the Neubauer and Hoffer cornstalk methods for determining mineral soil deficiencies. *Bull. Colo. agric. Exp. Sta.*, 390, 1-59.

STEWART, R. 1932. The Mitscherlich, Wiessmann and Neubauer methods of determining the nutrient content of soils. *Tech. Commun. Bur. Soil Sci., Harpenden*, 25, 1-46.

Stutzer, A. 1914. Fünfjährige Düngungsversuche in Ostpreussen. Bericht über Düngeversuche, in den Jahren 1909 bis 1913 ausgeführt. *Arb. dtsch. LandwGes.* 258, 1-236.
Süchting, H. 1939. Untersuchungen über die Ernährungsverhältnisse des Waldes. IV. Prüfung ausgewählter Waldböden auf Nährstofflieferung durch Vegetationsversuche mit Lärche, Kiefer und Fichte sowie auf Nährstofflöslichkeit durch chemische Untersuchungsmethoden. *Bodenk. PflErnähr.*, 13, 73-117.
——— 1942. Untersuchungen über die Ernährungsverhältnisse des Waldes. VIII. Zur Methodik der Bestimmung der Nährstoffdynamik in Waldböden. *Bodenk. PflErnähr.*, 28, 340-361.
———, Jessen, W., and Maurmann, G. 1938. Über die Wirkung der Düngung bei Waldböden, II. (Prüfung der Nährstoffwirkung nach physiologischen Methoden.) *Bodenk. PflErnahr.*, 8, 272-335.
Suzuki, U. 1897. On an important function of leaves. *Bull. Coll. Agric. Tokyo*, 3, 241-252.
Tacke, B. 1910. Über die botanische und chemische Zusammensetzung verschiedener Heusorten. *Fühlings landw. Ztg.*, 59, 361-374.
——— 1910a. Werden die Moorwiesen ausreichend gedüngt? *Mitt. Ver. Moork., Berl.*, 28, 16-20.
——— 1910b. Werden die Moorwiesen genügend gedüngt? *Mitt. Ver. Moork., Berl.*, 28, 313-317.
Tam, R. K., and Clark, H. E. 1943. Effect of chloropicrin and other soil disinfectants on the nitrogen nutrition of the pineapple plant. *Soil Sci.*, 56, 245-261.
Tanada, T., and Dean, L. A. 1942. Boron in some Hawaiian soils and crops. *Hawaii. Plant. Rec.*, 46, 65-74.
Teakle, L. J. H. 1942. Copper deficient soils in Western Australia. *J. Aust. Inst. agric. Sci.*, 8, 70-72.
——— 1944. Molybdenum as a fertiliser in Western Australia. *J. Agric. W. Aust.*, 21, 335-339.
———, Johns, H. K., and Turton, A. G. 1943. Experiments with micro-elements for the growth of crops in Western Australia. IX. Copper deficiency of currants at Gingin and its correction. *J. Dep. Agric. W. Aust.*, 20, 171-184.
———, Morgan, E. T., and Turton, A. G. 1941. Experiments with micro-elements for the growth of crops in Western Australia. III. Experiments with potatoes, vegetables and other crops in the Albany district. *J. Dep. Agric. W. Aust.*, 18, 96-125.
———, Thomas, I., and Turton, A. G. 1941. Experiments with micro-elements for the growth of crops in Western Australia. 1. Experiments in the wheat belt with cereals. *J. Dep. Agric. W. Aust.*, 18, 70-86.
——— and Turton, A. G. 1943. The copper, manganese, and zinc content of subterranean clover and oats in Western Australia. *J. Dep. Agric. W. Aust.*, 20, 238-259.
———, and Throssell, G. L. 1940. Experiments on copper deficient land at Dandaragan, Western Australia. *J. Dep. Agric. W. Aust.*, 17, 161-173.
Thoday, D. 1909. Experimental researches on vegetable assimilation and respiration. V. — A critical examination of Sachs' method for using increase of dry weight as a measure of carbon dioxide assimilation in leaves. *Proc. roy. Soc. B*, 82, 1-55.
Thomas, W. 1929. Balanced fertilizers and Liebig's law of the minimum. *Science* (*N.S.*), 70, 382-384.
——— 1930. The conception of balance with respect to the absorption of nitrogen, phosphorus and potassium by plants and the influence of the level of nutrition. *Science* (*N.S.*), 72, 425-427.
——— 1932. The reciprocal effects of nitrogen, phosphorus, and potassium as related to the absorption of these elements by plants. *Soil Sci.*, 33, 1-20.
——— 1934. Misconceptions relative to the mineral composition of plants. *Science* (*N.S.*), 80, 587.
——— 1936. Mathematical expression of equilibrium between nitrogen and phosphoric acid in plants. *Science* (*N.S.*), 84, 422-423.
——— 1937. Foliar diagnosis: principles and practice. *Plant Physiol.*, 12, 571-599.

———— 1938. Foliar diagnosis : its relation to the optimum nutrition of the potato. *Plant Physiol.*, 13, 677-694.
———— 1938a. Foliar diagnosis : application of the concepts of quantity and quality in determining response to fertilizers. *Proc. Amer. Soc. hort. Sci.*, 35, 269-272.
———— 1938b. Mathematical expression of equilibrium between lime, magnesia and potash in plants. *Science* (*N.S.*), 88, 222-223.
———— 1945. Present status of diagnosis of mineral requirements of plants by means of leaf analysis. *Soil Sci.*, 59, 353-374.
———— and Anthony, R. D. 1927. Eliminating some of the variables in apple fertilizer experiments. *Proc. Amer. Soc. hort. Sci.*, 23, 81-87.
— ——— and Mack, W. B. 1938. Foliar diagnosis in relation to development and fertilizer treatment of the potato. *J. agric. Res.*, 57, 397-414.
———— ———— 1939. Control of crop nutrition by the method of foliar diagnosis. *Bull. Pa agric. Exp. Sta.* 378, 1-33.
———— ———— 1939a. A foliar diagnosis study of the influence of calcium from two sources, lime and superphosphate. *J. agric. Res.*, 58, 685-693.
———— ———— 1939b. The foliar diagnosis of *Zea mays* subjected to differential fertilizer treatment. *J. agric. Res.*, 58, 477-491.
———— ———— 1939c. Foliar diagnosis : physiological balance between the bases lime, magnesia, and potash. *Plant Physiol.*, 14, 699-715.
———— ———— 1939d. Foliar diagnosis : nutritional differences affecting the yields of potatoes from similarly treated plots. *Proc. Amer. Soc. hort. Sci.*, 36, 573-589.
———— ———— 1939e. A foliar diagnosis study of the effect of three nitrogen carriers on the nutrition of *Zea mays*. *J. agric. Res.*, 59, 303-313.
———— ———— 1939f. Foliar diagnosis : the influence of the soil on the action of fertilizers. *Plant Physiol.*, 14, 75-92.
———— ———— 1940. Foliar diagnosis of differentially fertilized greenhouse tomatoes with and without manure. *J. agric. Res.*, 60, 811-832.
———— ———— 1940a. Salient features of the method of foliar diagnosis. *Proc. Amer. Soc. hort. Sci.*, 37, 253-260.
———— ———— 1941. Foliar diagnosis in relation to soil heterogeneity. *Soil Sci.*, 52, 455-468.
———— ———— 1941a. A foliar diagnosis study of greenhouse tomato plants showing symptoms of streak disease. *Proc. Amer. Soc. hort. Sci.*, 39, 319-328.
———— ———— 1941b. A foliar diagnosis study of the nutrition of greenhouse tomatoes in relation to the incidence of a disease. *Bull. Pa agric. Exp. Sta.* 405, 1-17.
———— ———— 1941c. Foliar diagnosis study of climatic influences on the nutrition of spring and fall grown greenhouse tomatoes. *Plant Physiol.*, 16, 117-144.
———— ———— 1941d. Susceptibility to disease in relation to plant nutrition. *Science* (*N.S.*), 93, 188-189.
———— ———— 1943. Foliar diagnosis in relation to plant nutrition under different conditions of weather and soil reaction. *Soil Sci.*, 56, 197-212.
———— ———— 1943a. Comparison of the nutrition of greenhouse and field grown tomatoes with respect to the fertilizer elements. *Proc. Amer. Soc. hort. Sci.*, 42, 545-546.
———— ———— 1944. The effect of different carriers of nitrogen on the nutrition of the potato. *Proc. Amer. Soc. hort. Sci.*, 44, 346-354.
———— ———— 1944a. Misconceptions relative to the method of foliar diagnosis. *Proc. Amer. Soc. hort. Sci.*, 44, 355-361.
———— ————, and Cotton, R. H. 1942. Foliar diagnosis in relation to irrigation. *Proc. Amer. Soc. hort. Sci.*, 40, 531-535.
———— ———— ———— 1943. Leaf analysis as a means of determining the fertilizer requirement of crops. *Amer. Fertil.*, 98 (4), 5-7, 26, 28.
———— ———— ———— 1943a. Nitrogen, phosphorus, and potassium nutrition of tomatoes at different levels of fertilizer application and of irrigation. *Proc. Amer. Soc. hort. Sci.*, 42, 535-544.

THOMAS, W., MACK, W. B., and RAHN, E. M. 1944. Foliar diagnosis and plant nutrition in fertilizer placement experiments. *J. Amer. Soc. Agron.*, 36, 889-902.
THORNE, D. W., and WALLACE, A. 1944. Some factors affecting chlorosis on high-lime soils : I. Ferrous and ferric iron. *Soil Sci.*, 57, 299-312.
THORNTON, S. F. 1931. Experiences with the Neubauer method for determining mineral nutrient deficiencies in soils. *J. Amer. Soc. Agron.*, 23, 195-208.
——— 1931a. The Neubauer method as applied to the determination of the availability of phosphate materials. *J. Ass. off. agric. Chem., Wash.*, 14, 292-295.
——— 1932. A field and laboratory test on plant material for diagnosing phosphorus deficiencies. *Bull. Ind. agric. Exp. Sta.* 355, 1-20.
——— 1933. A simple and rapid chemical test on plant material as an aid in determining potassium needs. *J. Amer. Soc. Agron.*, 25, 473-481.
——— 1933a. A simple and rapid chemical test on plant material as an aid in determining potassium needs. *Bull. Ind. agric. Exp. Sta.* 384, 1-20.
———, CONNER, S. D., and FRASER, R. R. 1934. The use of rapid chemical tests on soils and plants as aids in determining fertilizer needs. *Circ. Ind. agric. Exp. Sta.* 204, 1-16 (revised 1939).
TOKUOKA, M., and DYO, S. 1938. Influence of copper on the growth of lowland rice plants. Second Report :—Water Cultivation. [Japanese.] *J. Soc. trop. Agric. Taiwan*, 10, 9-15.
TOLLENS, B. 1902. The ash constituents of plants ; their estimation and their importance to agricultural chemistry and agriculture. Part II.—Importance of ash analysis to plant physiology and agricultural chemistry. *Exp. Sta. Rec.*, 13, 305-317.
TRELEASE, S. F., and TRELEASE, H. M. 1938. Selenium as a stimulating and possibly essential element for indicator plants. *Amer. J. Bot.*, 25, 372-380.
TRUFFAUT, G., and BEZSSONOFF, N. 1927. Mesure de l'assimilabilité de divers phosphates par leur action sur la fixation bactérienne de l'azote. *C.R. Acad. Sci., Paris.* 185, 85-86.
TRUNINGER, E. 1944. Zur Frage der Magnesiadüngung. [French summary.] *Landw. Jb. Schweiz*, 58, 131-148.
——— 1944a. Versuche und Untersuchungen über die Wirkungen des Bors als Spurenelement. [French summary.] *Landw. Jb. Schweiz*, 58, 1-36.
——— and VON GRÜNIGEN, F. 1935. Ueber den Mineralstoffgehalt einiger unserer wichtigsten Wiesenpflanzen mit besonderer Berücksichtigung der physiologischen Bedeutung des Kalis im Wiesenfutter. [French summary.] *Landw. Jb. Schweiz* 49, 101-127.
ULRICH, A. 1941. Nitrate test. A guide to nitrogen fertilization of sugar beets. *Sugar Beet Bull.*, 5, 77-78.
——— 1942. Potassium content of grape leaf petioles and blades contrasted with soil analyses as an indicator of the potassium status of the plant. *Proc. Amer. Soc. hort. Sci.*, 41, 204-212.
——— 1942a. Nitrate content of grape leaf petioles as an indicator of the nitrogen status of the plant. *Proc. Amer. Soc. hort. Sci.*, 41, 213-218.
——— 1942b. Plant analysis as a diagnostic procedure. *Amer. Fertil.*, 97 (7), 10.
——— 1943. Plant analysis as a diagnostic procedure. *Soil Sci.*, 55, 101-112.
——— 1943a. The relationship of nitrogen to the formation of sugar in sugar beets. *Proc. Amer. Soc. Sugar Beet Technol.* 3, 66-80.
——— 1944. Plant nutrient survey of sugar beets for 1943. Duplicated. Published by the Division of Plant Nutrition, University of California, Berkeley, Calif., pp. A-G + 37.
——— 1944a. Critical phosphorus and potassium levels in Ladino clover plants. *J. Amer. Soc. Agron.*, 36, 994.
VAIDYA, V. G. 1938. The seasonal cycles of ash, carbohydrate and nitrogenous constituents in the terminal shoots of apple trees and the effects of five vegetatively propagated rootstocks on them. *J. Pomol.*, 16, 101-126.
VANSELOW, A. P. 1945. The minor element content of normal, manganese-deficient, and manganese-treated English walnut trees. *Proc. Amer. Soc. hort. Sci.*, 46, 15-20.
VEALE, P. T. 1942. Nutritional information from plant tissue tests. *Better Crops with Plant Food*, 26 (5), 10-13, 42-45.

VINALL, H. N., and WILKINS, H. L. 1936. The effect of fertilizer applications on the composition of pasture grasses. *J. Amer. Soc. Agron.*, 28, 562-569.
VINET, E. 1931. Le diagnostic ligneux des plantes vivaces (vignes) et sa relation avec le diagnostic foliaire. *C.R. Acad. Agric. Fr.*, 17, 954-959.
——— 1932. Le diagnostic ligneux des plantes vivaces (vignes) dans ses rapports avec la production. *C.R. Acad. Agric. Fr.*, 18, 806-814. *Progr. agric. vitic.* 98, 374-379.
——— 1932a. Le diagnostic ligneux de la vigne et la production à venir. *C.R. Acad. Agric. Fr.*, 18, 1061-1069.
——— 1933. La fumure annuelle de la vigne et l'accumulation des effets fertilisants, d'après le diagnostic ligneux (1). *C.R. Acad. Agric. Fr.*, 19, 938-946.
——— 1934. Contribution à l'étude de l'alimentation minérale de la vigne—sur l'efficacité comparée de quelques engrais azotés. *C.R. Acad. Agric. Fr.*, 20, 766-771.
——— 1935. Contribution à l'étude de l'alimentation minérale de la vigne. (Action de la fumure sur le développement du bois de taille en rapport avec sa composition minérale et son aptitude à la production.) *C.R. Acad. Agric. Fr.*, 21, 911-919.
——— 1937. Action sur la vigne de la fumure carencée en potasse ou en azote. *C.R. Acad. Agric. Fr.*, 23, 774-782.
——— 1938. Sur la fumure de la vigne et le rajeunissement du système radiculaire.—Remise en état d'une parcelle non fumée et d'une autre carencée en potasse. *C.R. Acad. Agric. Fr.*, 24, 854-861.
——— 1942. Contribution à l'étude du rôle physiologique du potassium chez la vigne. *Ann. agron.* (*N.S.*), 12, 224-239.
——— and LEMESLE, —. 1930. Viticulture. Sur le contrôle de l'action des engrais par la diagnostic foliaire et l'analyse des bois aoûtés (1). *C.R. Acad. Agric. Fr.*, 16, 539-545.
——— ——— 1930a. Essais sur les engrais appliqués à la vigne. [quoted by Wetzel, *Ernähr. Pfl.*, 27, 17-18].
VITTUM, M. T. 1941. Plant tissue tests as an aid in the study of long-time fertility experimental plots. *Proc. nat. Jt. Comm. Fert. Appl.*, 17, 41.
DE VRIES, O. 1939. De magnesium-verzorging der cultuurplanten. *Chem. Weekbl.*, 36, 593-598.
WADLEIGH, C. H. 1938. Metabolism in the cotton plant. *Bull. Ark. agric. Exp. Sta.* 351. *Rep. for* 1936-7, 35-36.
——— 1944. Growth status of the cotton plant as influenced by the supply of nitrogen. *Bull. Ark. agric. Exp. Sta.*, 446, 1-138.
WAGNER, F. 1931. Wissenschaftliche Obstbaum- und Beerenobstdüngungsversuche in Weihenstephan. *Arb. dtsch. LandwGes.* 377, 1-111.
WAGNER, P. 1907. Forschungen auf dem Gebiete der Weinbergdüngung. *Arb. dtsch. LandwGes.* 124, I-VIII + 1-152.
——— 1909. Versuche über Wiesendüngung. *Arb. dtsch. LandwGes.* 162, 1-106.
——— 1911. Kann man aus der chemischen Untersuchung der Rebblätter Aufschluss über den Düngungszustand des Weinbergs erhalten? *Ber. landw. VersSta. Darmstadt.* [quoted by Herschler, 1933].
——— 1915. Die Wirkung von Stallmist und Handelsdüngern nach den Ergebnissen von 4-14 jährigen Versuchen. *Arb. dtsch. LandwGes.* 279, 1-544.
——— 1921. Die Düngung der Wiesen nach den Ergebnissen von 4-14 jährigen Versuchen. *Arb. dtsch. LandwGes.* 308, 1-141.
——— 1924. Meine Erfahrungen auf dem Gebiete der Rebendüngung. *Mitt. dtsch. LandwGes.*, 39, 131-132.
WALL, M. E. 1939. The rôle of potassium in plants: I. Effect of varying amounts of potassium on nitrogenous, carbohydrate, and mineral metabolism in the tomato plant. *Soil Sci.*, 47, 143-161.
——— 1940. Micro determination of some constituents of plant ash. *Plant Physiol.* 16, 537-545.
——— 1940a. The rôle of potassium in plants. Thesis, Rutgers University, N.J.
——— 1940b. The rôle of potassium in plants: II. Effect of varying amounts of potassium on the growth status and metabolism of tomato plants. *Soil Sci.*, 49, 315-331.

WALLACE, T. 1928. Investigations on chlorosis of fruit trees. II.—The composition of leaves, bark and wood of current season's shoots in cases of lime-induced chlorosis. *J. Pomol.*, 7, 172-183.
———— 1928a. The effects of manurial treatments on the chemical composition of gooseberry bushes. I. Effects on dry matter, ash and ash constituents of leaves and stems of terminal shoots and of fruits ; and on total nitrogen of fruits. *J. Pomol.*, 7, 130-145.
———— 1928b. Investigations on chlorosis of fruit trees, III. A chlorosis of plums due to potassium deficiency. *J. Pomol.*, 7, 184-198.
———— 1929. Experiments on the manuring of fruit trees. III. The effects of deficiencies of potassium, calcium and magnesium, respectively, on the contents of these elements, and of phosphorus in the shoot and trunk regions of apple trees. *J. Pomol.*, 8, 23-43. Abridged in *Rep. agric. hort. Res. Sta. Bristol for* 1929, 47-58.
———— 1929a. Leaf scorch of fruit trees. Empire Marketing Board unnumbered publication, pp. 5.
———— 1929b. Experiments on the control of leaf scorch on red currant and gooseberry bushes at Hartlip, near Sittingbourne. *Kent Fmrs' J.*, 25, 172, 174, 175, 177.
———— 1930. Some effects of deficiencies of essential elements on fruit trees. *Ann. appl. Biol.*, 17, 649-657.
———— 1932. Chemical investigations relating to potassium deficiency of fruit trees. *J. Pomol.*, 9, 111-121. *Rep. agric. hort. Res. Sta. Bristol for* 1931, 17-27.
———— 1938. Manuring of fruit crops. *Bull. Minist. Agric. Lond.* 107, 1-50 + vi.
———— 1939. Magnesium-deficiency of fruit trees. *J. Pomol.*, 17, 150-166.
———— 1940. Chemical investigations relating to magnesium deficiency of fruit trees. *J. Pomol.*, 18, 145-160.
———— 1940a. Magnesium deficiency of fruit trees : the comparative base status of the leaves of apple trees and of gooseberry and black currant bushes receiving various manurial treatments under conditions of magnesium deficiency. *J. Pomol.*, 18, 261-274.
———— 1941. Magnesium deficiency of fruit and vegetable crops. *Rep. agric. hort. Res. Sta. Bristol for* 1940, 24-28.
———— 1943. The diagnosis of mineral deficiencies in plants. A colour atlas and guide. His Majesty's Stationery Office, London, pp. vi + 116.
———— 1943a. Mineral deficiencies in vegetable and fruit crops. Visual methods of diagnosis. *Occas. Publ. sci. Hort.*, 4, 38-40.
———— 1944. The diagnosis of mineral deficiencies in plants. A colour atlas and guide supplement. His Majesty's Stationery Office, London, pp. 48.
————, JONES, J. O., and PLANT, W. 1942. Note on the composition of potato haulm from manurial treatments D, E, F, H. *Rep. agric. hort. Res. Sta. Bristol for* 1941, 39.
———— and MANN, C. E. T. 1926. Investigations on chlorosis of fruit trees. 1.—The composition of apple leaves in cases of lime-induced chlorosis. *J. Pomol.*, 5, 115-123.
———— and OSMOND, D. A. 1941. A preliminary note on the comparative effects of sulphate of potash, muriate of potash and kainit on various fruit plants. *Rep. agric. hort. Res. Sta. Bristol for* 1940, 13-18.
———— and PROEBSTING, E. L. 1933. The potassium status of soils and fruit plants in some cases of potassium deficiency. *J. Pomol.*, 11, 120-148.
WALLIHAN, E. F. 1944. Chemical composition of leaves in different parts of sugar maple trees. *J. For.*, 42, 684.
WALSH, T. 1942. Soil fertility studies, Part II. The assessment of soil fertility. *J. Dep. Agric. Éire*, 39, 277-306.
———— and CLARKE, E. J. 1942. A chlorosis of tomatoes. *J. Dep. Agric. Éire*, 39, 316-325.
———— and CULLINAN, S. J. 1945. Investigations on marsh spot disease in peas. *Min. Proc. R. Irish Acad. B.*, 50, 279-285.
WALTMAN, C. S. 1944. Effects of fall application of nitrogen fertilizer on the soluble nitrogen and phosphate phosphorus content of dormant peach twigs. *Bull. Ky agric. Exp. Sta.* 457, 1-16.
WANDER, I. W., and GOURLEY, J. H. 1943. Effect of heavy mulch in an apple orchard upon several soil constituents and the mineral content of foliage and fruit. *Proc. Amer. Soc. hort. Sci.*, 42, 1-6.

Wann, F. B. 1934. Nature and cause of chlorosis in Utah and practical methods of control. *Bull. Utah agric. Exp. Sta.* 250, 41-42.
Wark, D. C. 1938. A method for testing nitrogen deficiency. *J. Aust. Inst. agric. Sci.*, 4, 208-210.
———— 1939. Tests on plant tissue as a guide to the soil's available nutrients. *J. Aust. Inst. agric. Sci.*, 5, 224-227.
Warne, L. G. G. 1934. The distribution of potassium in normal and scorched foliage. *Ann. Bot., Lond.*, 48, 57-67.
Waugh, J. G., and Cullinan, F. P. 1941. The nitrogen, phosphorus, and potassium content of peach leaves as influenced by soil treatments. *Proc. Amer. Soc. hort. Sci.*, 38, 13-16.
Weinhold, A. 1862. Analyse von Unkräutern des Bodens der Versuchsstation Chemnitz. *Landw. VersSta.* 4, 188-193.
———— 1864. Ueber die Uebereinstimmung der Zusammensetzung von Pflanzenaschen und derjenigen des Bodens. *Landw. VersSta.*, 6, 50-57.
Welton, F. A., Morris, V. H., and Gerdel, R. W. 1926. Corn stalks vs. field plots as a guide to the fertility requirements of the corn crop. *Bull. Ohio agric. Exp. Sta.* 397, 285-302.
Wiegner, G. 1933. Choix de méthodes uniformes et appropriées pour la détermination des besoins d'engrais des terrains. [French and German.] *Conf. intern. Engr. chim.*, 2, 225-228.
Wiessmann, . 1927. Die Bestimmung des Nährstoffgehalts der Böden durch den Gefässversuch. *Ernähr. Pfl.*, 23, 386-387.
Wilfarth, —. 1897. Die Anwendung des Vegetationsversuches zur Bodenanalyse. *Chem. Ztg.*, p. 819. [quoted in 1898 *Biederm. Zbl.*, 27, 223-224]. *Verh. dtsch. Naturf.* Ärzte., 197, 108-110. [quoted in 1898 : *Chem. Zbl.*, 69 (II), 222-223].
———— 1898. *Biederm. Zbl.* [quoted by Stahl-Schröder, 1904].
Winogradsky, S. 1928. Sur l'application agronomique d'une épreuve microbiologique. *C.R. Acad. Sci., Paris*, 187, 161-165.
Wolf, B. 1940. Factors influencing availability of boron in soil and its distribution in plants. *Soil Sci.*, 50, 209-217.
———— 1942. Chemical factors influencing the set of Henderson lima beans. *J. Amer. Soc. Agron.*, 34, 646-650.
———— 1943. Rapid determination of soluble nutrients in soil and plant extracts by means of a photoelectric colorimeter. *Industr. Engng Chem., Anal. Ed.*, 15, 248-251.
———— 1944. Determination of nitrate, nitrite and ammonium nitrogen. Rapid photometric determination in soil and plant extracts. *Industr. Engng Chem. Anal. Ed.*, 16, 446-447.
———— 1944a. Rapid photometric determination of total nitrogen, phosphorus, and potassium in plant material. *Industr. Engng Chem., Anal. Ed.*, 16, 121-123.
———— 1945. Amounts of fertilizer elements removed by peas at three stages of growth. *J. Amer. Soc. Agron.*, 37, 292-296.
Wolff, E. 1868. Bericht über die in den Jahren 1866 and 1867 ausgeführten Vegetationsversuche in wässriger Lösung der Nährstoffe. *Landw. VersSta.*, 10, 349-379.
———— 1876. Ueber das Minimum der Nährsalze. Tagebl. 49. Vers. dtsch. Naturf. Ärzte in Hamburg. Beil., 170. [quoted in 1878 : *J. Ber. Fortschr. AgrikChem.*, 18/19, 250-251.]
———— 1877. [Versuche in Wassercultur über den Bedarf der Haferpflanzen an Stickstoff-Nahrung und an fixen Nährstoffen.] *Landw. VersSta.*, 20, 395-398.
Woodbridge, C. G. 1937. The boron content of apple tissues as related to drought spot and corky core. *Sci. Agric.*, 18, 41-48.
Woodward, T. E., Shepherd, J. B., and Tysdal, H. M. 1944. Yield and chemical content of alfalfa cut at different times of the day and night. *J. Amer. Soc. Agron.*, 36, 940-943.
Wright, C. H. 1939. Soil analysis. A handbook of physical and chemical methods. 2nd edition. Thomas Murby and Co., London, pp. x + 276.
Yates, F., and Watson, D. J. 1939. Factors influencing the percentage of nitrogen in the barley grain of Hoosfield. *J. agric. Sci.*, 29, 452-458.
Yuen, Q. H., and Hance, F. E. 1939. Nitrogen in the cane leaf. *Hawaii. Plant. Rec.*, 43, 163-207.

# SUBJECT INDEX


*Acer* spp. *see* red maple, sugar maple
Acetate buffer solution, extraction of plant material for analysis by, 38-40, 43, 87, 88, 102
Acetic acid, extraction of plant material for analysis by, 22, 23, 25, 33, 38, 39, 43, 76, 83, 85, 87, 93, 114
" Active " iron and manganese in plant, 21, 86, 87
Age—
  of leaves *see* leaf age
  of trees does not affect diagnosis by plant analysis, 45
Alcohol *see* ethyl alcohol
*Aleurites* spp. *see* tung
*Allium cepa see* onion
Aluminium, 80
Analysis of plant material
  methods for, 89
  speed, of, 115
*Ananas sativus see* pineapple
*Andropogon sorghum* var. *sudanense see* Sudan grass
*Apium graveolens see* celery
Apple (*Pyrus malus* and others) 11, 16, 20, 22, 23, 38, 45, 64, 66, 68-70, 77, 81, 87, 90-92, 97, 109, 113, 114
  corky core of, 45
Apricot (*Prunus armeniaca*), 23, 71
*Arachis hypogaea see* peanut
Arsenic, 31, 39, 80, 81
Artichoke (*Cynara scolymus*), 24
" Ash skeleton " analysis of plant material, 89
Ash weight as basis for expressing analytical results, 22, 24, 34, 89, 92
Asparagus (*Asparagus officinalis*), 24
*Astragalus* indicates selenium, 11, 44, 97
*Avena sativa see* oats.
Avocado (*Persea americana*), 20, 24, 86
*Axonopus affinis see* carpet grass

" Balance " in nutrient supply, 48, 49, 54-56, 107
Barley (*Hordeum vulgare*), 12, 15, 16, 24, 52, 53, 69-71, 77, 83, 84, 87, 88, 90, 97, 109-111
Bases, mutual replacement of, 58
Basswood (*Tilia* sp.), 97
Bean, *see also* field, French, lima, snap and white bean, 85, 86
Beech (*Fagus grandifolia*), 97
Beet (*Beta vulgaris*), 17, 24, 68, 70, 71, 77, 83, 90, 92, 97, 109
*Beta vulgaris see* beet, chard, mangold, sugar beet
Blackberry (*Rubus* spp.), 71
Black—
  currant (*Ribes nigrum*), 25
  gum (*Nyssa sylvatica*), 98
  raspberry (*Rubus occidentalis*), 38
Bleeding *see* exuded sap.
Blue grass (*Phleum pratense*), 83
Boron, 20, 23-36, 39, 40, 45, 68-77, 86, 89, 90, 92, 100, 103, 109, 111, 112
  proportion in expressed sap, 86
Botanical composition of hay, relation to chemical composition, 17
Boysenberry (*Rubus* hybr.), 38
Bracken (*Pteridium aquilinum*), 20
*Brassica oleracea see* brussels sprouts, cabbage, cauliflower, kohl-rabi, rape, red cabbage, Savoy cabbage
*Brassica* spp. *see* charlock, mustard, rutabaga, swede, turnip
Broad bean *see* Field bean
Brussels sprouts (*Brassica oleracea*), 25
Buckwheat (*Fagopyrum esculentum*), 42, 71, 84, 85

Cabbage (*Brassica oleracea*), 25, 71, 77, 83, 98
Cacao (*Theobroma cacao*), 25, 38, 42, 77, 90, 92, 98, 109, 110
Calcifugy, 11
Calcium, 14, 20, 27-31, 34, 35, 39, 40, 56, 65, 67, 68, 71-75, 80, 82, 85-87, 89, 90, 98-101, 107, 109-112, 114
Calendula (*Calendula officinalis*), 25
Cape-weed, 16
*Capsicum frutescens see* red pepper
Carbohydrate—
  accumulation, index of, 43
  content, relation to nutritional diagnosis, 100
Carbon/nitrogen balance indicated by leaf colour 43, 113
Carpet grass (*Axonopus affinis*), 25
Carrot (*Daucus carota*), 25, 38, 98
*Carya pecan see* pecan
Cattle, deficiency diseases in, 44
Cauliflower (*Brassica oleracea*), 71, 77
Celery (*Apium graveolens*), 26, 71, 77, 83, 98
Cereals *see also* barley, maize, etc., 17, 26, 38, 42-45, 53, 56, 57, 59, 65, 68, 84-86, 112-114
Chard (*Beta vulgaris* var. *cicla*), 26
Charlock (*Brassica sinapis*) as indicator plant, 10
*Chenopodium album*, 16
Cherry (*Prunus cerasus* and others), 20, 26, 38
Chestnut oak (*Quercus montana*), 98
Chicory (*Cichorium intybus*), 71
Chlorine, 20, 24, 27, 34, 40, 85, 108, 114
Chlorophyll determination to assess nitrogen status, 11
Chlorosis, 21, 46, 85, 87, 88
*Cichorium intybus see* chicory
Citrus, 20, 26, 38, 42, 64, 66, 77, 86, 98
  spp. *see* grapefruit, lemon, orange
Cleaning of plant material samples, 13, 80, 81
Climate, effect on nutrient requirements, *see also* weather, 14, 17, 43, 45
Clover, *see also* white and other clovers (*Trifolium* spp.), 42, 45, 77, 84, 85, 87, 98
Cobalt, 44
Coffee (*Coffee* spp.), 71
Colorimetric methods of analysis, 19, 62, 84, 89
Comparison of " good " and "poor" plants in field as basis of diagnosis, 43, 59, 112
" *Compositions types*," 15, 59

Conducting tissues, diagnostic analysis of, 67, 76
Contamination of plant material samples, 21, 69, 80-82
during drying, 31
during grinding, 81, 82
removal of, 80, 81
Copper, 20, 23, 27, 29, 31-33, 36, 38, 39, 44, 45, 59, 64, 66, 73, 74, 80, 82, 92, 96, 97, 99, 101-103, 110
" Corky core " of apple, 45
Corsican pine (*Pinus laricio* var. *Corsicana*), 98
Cotton (*Gossypium hirsutum*), 26, 42, 43, 65, 71, 82-84, 86, 94, 111, 114
Cowpea (*Vigna sinensis*), 26
Criteria for selecting diagnostic technique, 61-64
" Critical percentage," 57, 58, 96, 97, 100, 106
" Crude chlorophyll " analysis, 42, 88
Crusher juice of sugar cane analysed for diagnostic purposes, 44, 85, 86, 96
Cucumber (*Cucumis sativus*), 71
*Cucumis* spp. *see* cucumber, musk melon
*Cucurbita* sp. *see* squash
Cultivation, effect on nutrient content of plant material, 41
*Cynara scolymus see* artichoke

Date palm (*Phoenix dactylifera*), 86
*Daucus carota see* carrot.
Day length, effect on standard nutrient content values, 97
Deficiency—
definition, 47
diseases of plants identified by analysis, 19-21, 41, 112, 117
symptoms,
as method of diagnosis, 10, 19, 20, 116, 117
limiting values for nutrient content, 14, 37-40
relation to nutrient ratios within plant, 107-109
relation to plant nutrient content, 14, 19-21, 64, 69
relation to sampling for deficiency diagnosis, 69
Development, stage of *see* stage of development
" *Diagnostic foliaire* " *see* foliar diagnosis
" *Diagnostic ligneux* " 42
Diminishing returns, law of, 47
*Diospyros kaki, see* persimmon
Diseases—
effect on diagnosis by plant analysis, 113
effect on nutrition shewn by leaf analysis, 41
Dry weight as basis for expressing analytical results, 89-92
Drying—
effect on solubility of potassium in plant material, 87
of plant material samples, 81
Dust, contamination of plant material by, 80

*Echinochloa frumentacea see* Japanese millet
Electro-foliar diagnosis, 88
Elm (*Ulmus americana*), 71
Equivalents, as method of expressing analytical results, 41, 90, 108, 110, 111
Errors—
of diagnosis by plant analysis, 16, 62, 63, 68, 69
systematic *see* systematic errors
Ethyl alcohol, extraction of plant material by, 42, 88, 111
Expressed sap—
effect of varying pressure on composition, 86
proportion of boron in, 86
use for diagnosis *see also* crusher juice, 40, 42, 43, 65, 83-86, 91, 97, 98, 100
Expression of analytical results, methods of, *see also* ash weight, dry weight, fresh weight, leaf, oxides, plant, sap volume, 89-92
Extraction of plant material for analysis, *see also* acetate buffer solution, acetic acid, ethyl alcohol, formic acid, hydrochloric acid, sulphuric acid, water, 42, 61, 76, 82, 86-88, 91
Exuded sap, use for diagnosis, 40, 45, 83, 84, 88

*Fagopyrum esculentum see* buckwheat
*Fagus grandifolia see* beech
Fertilizer—
dosage, relation between responses to different, 47, 48, 93
materials, relation between responses to different, 93
placement, effect on soil analysis results, 10, 116
trials, *see* field trials.
Fertilizers—
response to, relation to plant composition, 46, 57, 63, 64, 91-117
seasonal changes in availability, 65
*Ficus carica see* fig.
Field—
bean (*Vicia faba*), 26, 71, 98
trials as method of deficiency diagnosis, 7, 17, 115
for setting up standard values for nutrient content of plant material, 13-15, 17, 18, 44, 45, 61-64, 93-95, 115, 117
interpretation of results by plant analysis, 19, 41, 42, 44, 45, 117
Fig (*Ficus carica*), 27, 71
Flax (*Linum usitissimum*), 27, 71, 98
" Foliar diagnosis," 41, 42, 63, 67, 68, 110-112, 116
Forage crops *see also* individual species, 84, 85
Forest trees *see also* individual species, 42, 65
nutritional diagnosis in, 9, 45, 59, 66, 94, 97, 98, 103, 106
Formic acid, extraction of plant material for analysis by, 85
*Fragaria* spp. *see* strawberry
*Fraxinus americana see* white ash
French bean (*Phaseolus vulgaris*), *see also* snap bean, etc., 20, 27, 70, 72
" Frenching " of tobacco, 20
Fresh weight, as basis for expressing analytical results, 22, 23, 25, 30, 31, 33, 34, 40, 89, 91, 97-106
Fruit—
colour, relation to leaf composition, 97, 113
trees, *see also* individual species, 47, 85, 97, 114, 116
Fruiting, effect on plant composition, 114
Fruits, deciduous, *see also* individual species, 77

Gallium, 72
Ganong leaf punch, *see* leaf punch
*Glycine soja see* soybean
" Good " and " poor " plants in field, comparison of composition as diagnostic technique, 43, 58, 112
Gooseberry (*Ribes grossularia*), 27, 42, 72, 113
*Gossypium hirsutum, see* cotton
Grape *see* vine
Grapefruit (*Citrus paradisi*), 20, 27, 38, 42, 67, 78, 86, 91, 92, 98, 109, 110, 113
Grasses, *see also* individual species, 43, 84
Grey speck disease of oats, 107
Grinding of plant material samples, 81
Growth—
factors affecting, 47, 53, 54
morphological types of, 47, 49

Hay analysis, 17, 94, 95, 99
*Helianthus* spp. *see* Jerusalem artichoke, sunflower
*Hevea brasiliensis see* rubber
Hickory (*Hicoria* spp.), 44, 45, 100, 102
Hop (*Humulus lupulus*), 16, 41, 72, 78, 94, 95
*Hordeum vulgare see* barley
Human nutrition, iodine in plants and, 44
Hydrochloric acid, extraction of plant material for analysis by, 21, 87

Illumination *see* day length, light
Indicator plants, 10, 11
Indium, 72
Injection of plants for deficiency diagnosis, 8, 21, 116
" Intensity of nutrition," 110
Interaction of nutrients, *see* " Balance " in nutrient supply, Interrelations . . .
" Internal starvation," 56
Interpretation of results of diagnostic plant analysis, 41, 57, 58, 61, 92-112
Interrelations of internal concentrations of different nutrients in relation to diagnosis, 13-15, 17, 38, 39, 44, 49, 57, 58, 93, 94
Iodine, 44
*Ipomoea batatas see* sweet potato
Iron, 21, 65, 72, 74, 75, 80-82 85-87 108, 109
  accumulation under conditions of potassium deficiency, 82
  " active," 21, 86
  ferrous and ferric compared, 85
  immobilized in conducting tissues, 46
  relation to manganese, 108, 109
Irrigation *see* water supply

Japanese millet (*Echinochloa frumentacea*), 72
Jerusalem artichoke (*Helianthus tuberosus*), 28
*Juglans regia see* walnut

" K-Ca-Mg unit," 110
Kidney bean *see* French bean
Kohl-rabi (*Brassica oleracea*), 72

*Lactuca sativa see* lettuce
*Lathyrus odoratus see* sweet pea
" Law—
  of diminishing returns," 47, 48
  of limiting factors," 47, 58
  of maximum," 13, 14
  of minimum " (Heinrich), 13
  of minimum " (Liebig), 47, 58, 96
  of restitution," 12
Lawn grasses, 43
Leaching of nutrients from plant material, 13, 80
Leaf—
  age, relation to sampling for diagnosis, 16, 61, 68 69
  area as basis for expressing analytical results, 90, 91
  as unit for expressing analytical results, 90, 91
  colour as index of C/N ratio, 43, 113
  discs, absorption of nutrients as diagnostic index, 11
  painting as method of deficiency diagnosis, 8, 21
  punch samples for diagnosis, 44, 69, 91
Leaves—
  as most suitable organs for diagnostic analysis, *see also* organs of plant, 16, 41, 67, 76
  different morphological types compared for diagnostic purposes, 68, 69
Legumes *see also* individual species, 78
Lemon (*Citrus limonia*), 28, 72
*Lespedeza*, 42
Lettuce (*Lactuca sativa*), 28, 69, 78, 83, 87, 88, 99
Light effect—
  on diagnosis by plant analysis, 58, 70, 113
  on meristematic activity, 47
  on plant composition, 17, 18, 112
Lima bean (*Phaseolus lunatus*), 78, 87
Lime-induced deficiencies, 21, 82, 108
Liming, effect on nutrition, 46
Limiting—
  factors, law of, 47, 58
  values for nutrient content of plant material *see* deficiency symptoms, limiting values; standard values.
*Linum usitatissimum see* flax
*Liriodendron tulipifera see* yellow poplar
Long Ashton tests, 45
Lucerne (*Medicago sativa*), 28, 39, 43, 65, 72, 78, 85, 100, 107, 111
Lupin (*Lupinus hartwegi*), 28, 72
Luxury consumption, 13, 14, 17, 18, 49, 54, 56, 57, 60, 64, 92, 107
*Lycopersicum esculentum see* tomato

Magnesium, 20, 22, 23, 25-40, 67-75, 77, 79, 85-87, 90, 92, 97, 101, 103, 106, 110, 111, 113, 114
Maize (*Zea mays*), 28, 39, 42, 43, 45, 65, 66, 72, 78, 82-86, 88, 100, 108
Manganese, 20, 23, 26-36, 39, 40, 71, 73-75, 82, 86, 98, 103, 107-109, 114
  " active," 21, 86
  deficiency, nitrate accumulation under, 82
  relation to iron, 108, 109
Mangold (*Beta vulgaris*), 16, 29, 39, 70, 72, 94, 100
Maximum—
  law of, 13, 14
  values for nutrient content of plant material, 17, 18, 59, 96
  yield, 47, 48
*Medicago sativa see* lucerne
*Melilotus indica see* sweet clover
Meristematic activity, 47, 49, 53, 56
Meristems, forms in which nutrients are utilized by, 82
Milo (*Sorghum vulgare*), 29
Minimal values for nutrient content of plant material, 12-14, 18, 57-59, 96, 97, 100, 101
Minimum, law of *see* " Law of Minimum."
Mitscherlich growth curves, 18, 47, 48
Mobilization of nutrients from older organs, 54, 56, 68
Molybdenum, 40, 75, 79
Morphological types
  of leaf *see* leaves, different morphological types of plant growth, 47, 49
Musk melon (*Cucumis melo*), 29
Mustard (*Brassica* sp.), 29, 72

NPK unit," 110 111
Nitrate—
  accumulation under conditions of manganese deficiency, 82
  determination for diagnosis, 42-44, 58, 65, 68, 83 84, 86, 87, 97, 98, 100, 103, 105, 112
Nitrogen—too numerous to be specified
  comparison of different fractions for diagnostic purposes, 83, 84
" *Normalgehaltszahl,*" 18

Nutrient supply—
from soil *see* soil nutrient supply
relation to nutrient content of plant, 49-57
relation to yield, 47, 48, 93, 94
*Nyssa sylvatica see* black gum

Oats (*Avena sativa*), 12-18, 29, 37, 39, 44, 59, 62, 66, 68, 70, 73, 78, 82, 83, 86, 88, 93, 94, 100, 107, 109, 111, 114
grey speck disease of, 107
Olive (*Olea europaea*), 29
Onion (*Allium cepa*), 29, 73, 78
*Oonopsis* indicates selenium, 11
Optimum—
levels for factors affecting growth, 47
values for internal nutrient concentration, 43, 92, 94, 96-106, 107, 110-112
Orange (*Citrus aurantium* and others), 20, 29, 73, 78
Organs of plant as samples for diagnostic analysis, comparison of, *see also* leaves, roots, as most suitable organs, 12-15, 17, 67-80
*Oryza sativa see* rice
Oxides, expression of analytical results in terms of, 89

Painting of leaves *see* leaf painting.
Parsley (*Petroselinum hortense*), 30
Pea (*Pisum sativum*), 30, 39, 42, 43, 73, 78, 86, 101
Peach (*Prunus persica*), 20, 30, 39, 66, 73, 78, 81, 87, 101, 116
Peanut (*Arachis hypogaea*), 20, 31, 68, 73, 86, 89, 101
Pear (*Pyrus communis* and others), 31, 64, 73, 102
Pecan (*Carya pecan*), 31, 68, 73, 91, 102
Periodical sampling *see* successive samples
*Persea americana see* avocado
Persimmon (*Diospyros kaki*), 73
Pests, effect on diagnosis by plant analysis, 113
*Petroselinum hortense see* parsley
*Phalaris minor*, 82
*Phaseolus* spp. *see* bean, French bean, lima bean snap bean, white bean
*Phleum pratense see* blue grass
*Phoenix dactylifera see* date palm
Phosphate determination for diagnosis, 43, 65, 70, 76, 84, 86, 87, 97-106
Phosphorus—too numerous to be specified
comparison of different fractions for diagnostic purposes, 84
Pine (*Pinus* spp.) *see also* Corsican, Scots and white pines, 20, 32, 57, 58, 109
Pineapple (*Ananas sativus*), 20, 32, 43, 58, 65, 67, 69, 73, 79, 84, 102
*Pinus* spp. *see* pine
*Pisum sativum see* pea
Plant—
as unit for diagnostic analysis, 67
as unit for expressing analytical results, 90
Plants, selection for sampling, 45, 64
Plum (*Prunus domestica*), 20, 32, 39, 64, 66, 73, 79, 102, 114
Polarographic methods of plant analysis, 89
*Polygonum convolvulus*, 16
*Populus tremuloides see* trembling aspen
Pot culture methods of deficiency diagnosis, 10, 15, 16, 18
Potassium—too numerous to be specified
Potassium solubility affected by drying plant material
Potato (*Solanum tuberosum*), 15-17, 20, 32, 39, 42, 43, 47, 58, 65, 74, 79, 83, 85-88, 92, 102, 109, 111
" Poverty adjustment," 57
" Primary index," 43, 44
Pruning, effect on nutrition shewn by plant analysis, 41
*Prunus* spp., *see* apricot, cherry, peach, plum
*Pteridium aquilinum see* bracken
Purdue tests, 42, 45, 82, 88, 89
*Pyrus* spp. *see* apple, pear

*Quercus* spp. *see* chestnut oak, red oak, white oak

Radish (*Raphanus sativus*), 33, 74, 84
Rainfall, effect on composition of plant material, 45, 81, 112
Random and selective sampling compared, 64, 68
Rape (*Brassica oleracea*), 84, 85
*Raphanus sativus see* radish
Rare earths, 107
in plants and soils, 44
Raspberry—
black (*Rubus occidentalis*), 38
red (*Rubus idaeus*), 79
Ratios of nutrients in plant material as diagnostic index, 14, 15, 19, 37-42, 49, 58, 67, 103, 112
Red—
cabbage (*Brassica oleracea*), 33
clover (*Trifolium pratense*), 74
currant (*Ribes sativum*), 33, 40, 74, 108
maple (*Acer rubrum*), 103
oak (*Quercus borealis*), 103
pepper (*Capsicum frutescens*), 33, 74
Regressions, use in diagnostic work, 63, 107
Remobilization of nutrients *see* mobilization
" Resistance formula," 48
Restitution, law of, 12
Re-utilization of nutrients *see* mobilization
*Rheum rhaponticum see* rhubarb
Rhubarb (*Rheum rhaponticum*), 20, 33
*Ribes* spp. *see* black and red currants, gooseberry
*Rice* (*Oryza sativa*), 33, 40, 74, 85
Root—
competition affects diagnosis by plant analysis, 45
crops, *see also* individual species, 47
Roots, as most suitable organs for diagnostic analysis *see also* organs of plant, 13, 68
Root-soluble nutrients, 9
Rootstock, effect on mineral composition of scion, 114
Rubber (*Hevea brasiliensis*), 58, 65, 79, 92, 96
*Rubus* spp. *see* blackberry, boysenberry, raspberry
Rutabaga (*Brassica* sp.), 74
Rye (*Secale cereale*), 9, 11, 33, 70, 74, 79, 103

*Saccharum officinarum see* sugar cane
Sampling for diagnosis *see* organs of plant, random and selective sampling, selection of plants, successive samples, time of day, time of year
Sand culture, use in diagnostic work, 18, 20, 45, 62
Sap, *see also* expressed sap, exuded sap, tracheal sap volume, as basis for expressing analytical results, 20, 91
Savoy cabbage (*Brassica oleracea*, 33
Scots pine (*Pinus sylvestris*), 103
*Secale cereale see* rye
Seedlings—
absorption of nutrients from solution after growth in soil as deficiency index, 11
use for biological soil analysis, 9, 59

Selection of plants for sampling, 45, 64
Selenium indicator plants, 11, 44, 66, 97
Silicon, 110, 112
Small grains, 79
Snap bean (*Phaseolus vulgaris*) *see also* French bean, 74, 79, 84
Sodium—26, 37, 70, 111
  hydroxide solution for washing leaves, 81
  in plant, interrelation with potassium, 14, 37, 39, 94
Soil—
  acidity in relation to diagnosis by plant analysis, 37
  analysis as method of deficiency diagnosis, 8-10, 14, 116, 117
    by biological methods, 9, 10
    by chemical methods, 8, 10, 43, 89
    compared with plant analysis for deficiency diagnosis, 14-16, 61, 116
  availability of nutrients in, 8-10
  contamination of plant material by, 80
  fixation of nutrients, 8, 114, 116
  nitrification in, 8, 44
  nutrient supply, seasonal changes in, 56, 57, 59, 65
  survey, *see* survey
  type, effect on diagnosis by plant analysis, 45, 113, 116
*Solanum tuberosum see* potato
Solution culture
  use to identify deficiency symptoms, 10, 20
  use for selecting diagnostic method, 62
*Sorghum* spp., 29, 42, 84, 85, 88
*Sorghum vulgare see* milo
Soybean (*Glycine soja*), 33, 40, 74, 79, 84, 85, 108, 109, 111
Spacing of plants, effect on composition, 14
Special plots, diagnosis by analysis of material from, 19, 115
Spectrographic methods of analysis, 19, 20, 62, 87, 89
Spinach (*Spinacia oleracea*), 33, 68, 79, 84, 87
Spray injury, 20
Sprays, contamination of plant material by, 80
Squash (*Cucurbita*) sp.), 86
Stage of development for taking diagnostic samples of plant material *see also* successive samples, time of year, 17, 56, 59, 65-67
" Stalk-test " method (Hoffer), 82
*Stanleya* indicates selenium, 11
Standard values for nutrient concentration in plant material, *see also* maximum values, minimal values, optimum values, ratios of nutrients, 12, 15-17, 43, 45, 57, 61, 85, 93-113, 115
Starch content, relation to diagnosis, 58
Statistical methods in diagnostic work, 62-64, 68, 83, 90, 93, 107
Storage quality of fruit, relation to composition, 97
Strawberry (*Fragaria chiloensis* and others), 34, 69, 74, 86, 114
Subterranean clover (*Trifolium subterraneum*), 64, 79, 96, 103
Successive—
  crops, correlation between responses to fertilizers in, 62, 70
  samples of plant material during growing season for diagnosis, 41, 66, 67
  years, selection of diagnostic technique based on data from, 18, 62
Succulents, 65
Sudan grass (*Andropogon sorghum* var. *sudanense*), 83, 88
Sugar—
  beet (*Beta vulgaris*), 18, 34, 40, 42, 45, 69, 70, 75, 79, 83, 84, 86, 90, 91, 94, 103, 111
  cane (*Saccharum officinarum*) *see also* crusher juice, 34, 42-45, 64, 65, 67-69, 75, 79, 82, 84-86, 88, 92, 96, 104, 107, 110, 111, 113, 114
  determinations for nutritional diagnosis, 43, 82, 113
  maple (*Acer saccharum*), 68, 105
Sulphur, 30, 33, 40, 46, 73, 74, 80, 84-86, 100, 101
  comparison of different fractions for diagnostic purposes, 84
  treatment of soils, effect on nutrition, 46
Sulphuric acid, extraction of plant material for analysis by, 88
Sunflower (*Helianthus annuus*), 34, 75, 88
Survey, use of plant analysis in, 15, 19, 44, 45, 64
Swede (*Brassica napus*), 16, 34
Sweet—
  clover (*Melilotus indica*), 35
  corn (*Zea mays*), 43
  pea (*Lathyrus odoratus*), 35
  potato (*Ipomoea batatas*), 35, 42, 75
Systematic errors in diagnostic work, 63, 115

Tea (*Thea sinensis*), 15, 35, 75, 92
Temperature—
  effect on diagnosis by plant analysis, 58, 70, 113
  effect on meristematic activity, 47
  effect on plant composition, 49
Thallium, 20
*Thea sinensis see* tea
*Theobroma cacao see* cacao
*Tilia* sp. *see* basswood
Time—
  of day, effect on plant composition, 65
    for taking diagnostic samples of plant material, 65
  of year for taking diagnostic samples of plant material *see also* stages of development, successive samples, 14, 15, 45, 56, 61, 65-67
Tissue tests, 42-44, 81, 82, 84, 87-89
Tobacco (*Nicotiana tabacum*), 20, 35, 40, 70, 75, 80, 83, 86, 90, 109, 112
Tomato (*Lycopersicum esculentum*), 20, 35, 37, 40, 42, 43, 47, 65, 67, 68, 76, 80, 81, 83, 84, 88, 93, 105, 109, 113, 114
Top dressings, 57, 115, 116
  times determined by plant analysis, 43, 67
Toxicity—
  disorders of plants identified by analysis, 20
  symptoms, limiting values for nutrient content, 38-40
  relation to nutrient ratios within plant, 108, 109
  relation to plant nutrient content, 20-40
Trace elements, *see also* individual elements, 8, 10
Tracheal sap, use for diagnosis, 67, 88
Translocation of nutrients *see* mobilization
Trembling aspen (*Populus tremuloides*), 106
*Trifolium* spp. *see* clover, red clover, subterranean clover, white clover
" Triple analysis," 44, 93, 113
*Triticum vulgare see* wheat
Tung (*Aleurites* spp.), 20, 36, 40, 67
Turnip (*Brassica rapa*), 36, 76, 80

*Ulmus americana see* elm
Unelaborated fractions of nutrients determined as diagnostic indices, 42, 76, 82-85

Uptake of nutrients—
per unit area as diagnostic index, 18, 41, 90
relation to supply, 47-54
seasonal course of, 53, 54, 56, 59

Variability of diagnostic results by different techniques, 13, 62-64, 68, 69, 83, 91
Varietal differences—
effect on diagnosis by plant analysis, 114
in composition, 21, 38, 85, 86, 96, 110, 113, 114
in deficiency symptoms, 10
Vegetable crops *see also* individual species, 116
*Vicia faba see* field bean
*Vigna sinensis see* cowpea
Vines (*Vitis* spp.), 16, 20, 27, 64, 66, 68, 69, 72, 78, 83, 98, 109-111, 113, 114
*Vitis* spp., *see* vine

Walnut (*Juglans regia*), 36
Washing of plant material samples, 80, 81
Water—
content of plant as index of moisture relations, 113
culture *see* solution culture
extraction of plant material for analysis by, 31, 33, 34, 68, 74, 86, 87, 100
supply, effect on diagnosis by plant analysis, 58, 70, 112
effect on plant composition, 14, 17, 18, 41, 49, 112
Weather *see also* climate
effect on diagnosis by plant analysis, 18, 43, 60, 66, 113
effect on plant composition, 13, 16, 18, 41, 43, 49, 60
effect on soil nutrient supplies, 113
Weeds—
analysis for diagnosis, 12, 16, 115
deficiency symptoms in, 10
presence or absence as nutritional index, 11
Wheat (*Triticum vulgare*), 9, 13, 14, 16, 18, 36, 70, 76, 80, 83, 88, 90,107, 109-113
White—
ash (*Fraxinus americana*), 106
bean (*Phaseolus* sp.), 76, 87
clover (*Trifolium repens*), 40
oak (*Quercus alba*), 106
pine (*Pinus strobus*), 106, 112
"*Wirkungsmenge*," 48

*Xylorrhiza* indicates selenium, 11

Yellow poplar (*Liriodendron tulipiferum*), 106
Yield—
relation to nutrient supply, 47, 48, 93
relation to plant nutrient content, 57-59, 61, 62, 92-106, 110, 111

*Zea mays see* maize, sweet corn
Zinc, 24, 26, 27, 31, 36, 38-40, 45, 66, 71, 73, 75, 82, 87, 89, 101, 103

# AUTHOR INDEX


Acock, A. M., 9, 118
Adams, W. L., 129
Addoms, R. M., 143
Ahr, —, 17, 141
Aiyar, S. P., 33, 74, 85, 118
Akamine, —., 124
Alben, A. O., 102, 118
Albert, W. B., 29, 118
Albrecht, W. A., 81, 118
Aldrich-Blake, R. N., 98, 118
Alten, F. 126
Alvarino, J. E., 88, 113, 120
Alway, F. J., 17, 67, 72, 71, 92, 100, 118
Ames, J. W., 9, 66, 76, 82, 113, 116, 118, 147
Anderson, M. S., 8, 118
Anderssen, F. G., 8, 20, 32, 73, 92, 118, 141
Anthony, R. D., 20, 67, 91, 109, 126, 128, 151
Archibald, E., 38, 39, 118
Arnd, T., 8, 11, 118
Arnold, F., 148
Arnon, D. I., 86, 114, 118, 132
Askew, H. O., 23, 24, 27, 45, 68, 118, 119, 134, 147
Association of Official Agricultural Chemists, 89, 149
Atkinson, H. J., 43, 119
Atterberg, A., 13, 14, 17, 29, 37, 39, 67, 68, 72, 73, 94, 100, 101, 109, 119
Averna-Saccá, R., 21, 119

Bacon, C. W., 129
Bahrt, G. M., 26, 119
Baker, C. E., 42, 77, 78, 119
Baker, G. O., 10, 124
Balmukand, B., 48, 119
Bartholomew, R. P., 68, 72, 75, 119
Bathurst, A. C., 10, 64, 66, 77, 119
Batjer, L. P., 11, 22, 31, 38, 39, 45, 70, 97, 113, 114, 117, 119, 125, 139
Baule, B., 48, 119
Baver, L. D., 8, 119
Bear, F. E., 100, 111, 119, 132, 146
Beath, O. A., 11, 66, 120
Beauchamp, C. E., 42, 88, 107, 109-111, 113, 120
Beaumont, A. B., 74, 112, 120
Beck, A. B., 44, 120
Becker, J., 20, 120
Beeson, K. C., 44, 120, 139
Behrens, W. U., 7-9, 120
Benecke, W., 9, 120
Bennett, J. P., 21, 109, 120
Berger, K. C., 11, 77, 89, 120
Bezssonoff, N., 9, 152
Bidner, N., 27, 114, 146
Binnie, R. R., 71, 120
Blair, G. Y., 114, 126, 148
Blake, M. A., 87, 125
Blanck, E., 144
Blaser, R. E., 25, 120
Blume, J. M., 123, 131, 146
Bolas, B. D., 65, 89, 120, 147
Bonazzi, A., 120
Bonewitz, W., 143
Borden, R. J., 11, 44, 69, 85, 91, 96, 105, 110, 113, 120, 121
Boresch, K., 10, 33, 40, 69, 108, 121
Bortner, C. E., 35, 121
Bouat, A., 41, 80, 113, 140, 141
Bovschik, G., 9, 149
Bower, C. A., 110, 121
Bowling, J. D., 129
Boynton, D., 10, 11, 22, 26, 27, 38, 39, 42, 45, 64, 69, 77, 81, 89, 97, 102, 113, 116, 121, 122, 124, 146, 149
Brandenburg, E., 24, 29, 34, 39, 40, 68, 72, 75, 92, 100, 103, 114, 121
Bray, R. H., 84, 121
Brickley, W. D., 30, 32, 86, 121
Brinkerhoff, L. A., 122
Brown, B. A., 72, 122
Brown, B. E., 32, 39, 122
Brown, D. E., 129
Brown, D. S., 83, 122
Brown, H. D., 130
Brown, J. G., 42, 43, 45, 66, 78, 101, 112, 114, 116, 137
Brown, R. J., 45, 69, 84, 86, 122
Brown, S. M., 8, 10, 26, 28, 29, 38, 66, 72, 98, 123, 133
Bruinsma, J. R., 91, 103, 129
Bruner, F. H., 8, 119
Bryan, O. C., 8, 122
Burkhart, L., 11, 20, 31, 65, 68, 73, 86, 89, 101, 102, 114, 122, 124, 138, 144
Burrell, A. B., 22, 38, 42, 45, 64, 97, 113, 121, 122
Burrell, R. C., 130
Burström, H., 66, 69, 73, 122
Buslova, E. D., 8, 122
Butkevič, W., 9, 122
Byers, H. G., 11, 44, 122

Cain, J. C., 22, 45, 77, 121, 122, 131
Camp, A. F., 128
Capó, B. G., 7, 122
Carolus, R. L., 20, 25, 26, 30, 32, 33, 39, 43, 71, 74, 75, 82-87, 102, 103, 116, 122, 123
Carson, R. B., 114, 123
Cawthron Institute, 89, 123
Chaminade, R., 102, 103, 123
Chandler, R. F., Jr., 45, 65, 70, 94, 97, 98, 102, 103, 105, 106, 123, 141
Chandler, W. H., 24, 31, 36, 71, 79, 123, 132
Chapman, G. W., 21, 42, 58, 65, 69, 79, 92, 96, 123
Chapman, H. D., 8, 10, 26, 28-30, 38, 66, 70, 72, 73, 84, 98, 123, 137
Chemistry Department, Experiment Station, Hawaiian Sugar Planters' Association, 64, 65, 69, 91, 123
Chibnall, A. C., 65, 123
Chilean Nitrate Educational Bureau, 10, 123
Chittenden, E., 23, 97, 118, 123, 134, 147

Christensen, H. R., 9, 11, 123
Chucka, J. A., 75, 146
Clark, H. E., 38, 124, 150
Clarke, E. J., 75, 87, 124, 154
Clements, H. F., 43, 44, 68, 75, 104, 105, 110, 113, 124
Collins, E. R., 31, 73, 86, 93, 122, 124, 138
Colwell, W. E., 10, 124
Compton, O. C., 11, 38, 39, 42, 77, 113, 121, 124
Conner, S. D., 152
Conrad, J. P., 138
Cook, H. L., 42, 124, 148
Cook, R. L., 80, 83, 85, 87, 109, 111, 124
Cooper, H. P., 111, 124
Cooper, T. P., 56, 124
Cotton, R. H., 151
Craig, N., 42, 57, 65, 72, 85, 86, 94, 104, 105, 110, 113, 114, 124, 125
Cromwell, B. T., 20, 35, 125
Cros, L., 136
Crowther, F., 66, 94, 113, 114, 125
Cullinan, F. P., 29-31, 38, 39, 42, 45, 101, 117, 125, 155
Cullinan, S. J., 114, 154
Culp, F. B., 146

Daniel, H. A., 112, 125
Darrow, G. M., 42, 79, 125
Das, U. K., 88, 125
Davidson, O. W., 31, 38, 39, 77, 78, 87, 125
Davies, R. O., 42, 125
Davies, W. M., 28, 72, 125
Dean, L. A., 32, 73, 89, 125, 139, 150
Degman, E. S., 11, 22, 70, 119
Dickey, R. D., 20, 36, 125, 126
von Dikow, A., 13, 14, 19, 57, 59, 96, 97, 125
Dirks, B., 10, 125
Doi, M., 69, 125
Drake, M., 35, 40, 42, 70, 75, 109, 112, 125, 126
Draper, G. E., 132
Dregne, H. E., 28, 39, 100, 126
Drosdoff, M., 10, 20, 36, 40, 69, 93, 125, 126, 144
Duggan, J. B., 20, 126
Dulac, J., 41, 80, 113, 140
Dunbar, C. O., 20, 126
Dunne, T. C., 23, 126
Dyo, S., 74, 152

Eaton, F. M., 23-26, 71-76, 86, 114, 117, 126
Eaton, S. V., 10, 85, 88, 126
Eckstein, O., 58, 82, 126
Edgerton, —., 22, 126
Edgington, G., 45, 64, 147
Edler, —., 15, 126
Ehrenburg, P., 73, 126
Eichinger, —., 11, 126
Ellis, G. H., 139, 144
Emmerling, —., 17, 126
Emmert, E. M., 43, 57, 58, 67, 69, 76-80, 83, 84, 87-89, 93, 94, 99, 102, 105, 106, 112, 113, 114, 116, 126, 127
Empire Cotton Growing Corporation, 11, 82, 83, 127
English, L., 89, 144
Eppson, H. F., 120
Epstein, E., 23, 26, 31, 32, 36, 67, 127
Evans, H., 42, 88, 115, 127

Fagan, T. W., 125
von Feilitzen, H., 17, 127
Ferguson, W., 70, 127
Ferres, H. M., 7, 128
Finch, A. H., 8, 31, 67, 73, 99, 128
Finn, R. F., 45, 128, 141
Fitzpatrick, R. E., 23, 24, 128
Flügel, M., 144
Follett-Smith, R. R., 34, 92, 128
Fonder, J. F., 65, 85, 128
Forrest, L. A., 138
Forster, H. C., 66
Fraps, G. S., 7, 66, 100, 128
Fraser, R. R., 152
Frear, D. E. H., 67, 91, 128
Fred, E. B., 141
Friske, K., 145
Fudge, B. R., 20, 27, 39, 42, 69, 77, 86, 113, 114, 128
Fudge, L. F., 128

Gaddum, L. W., 26, 36, 89, 128
Gallagher, P. H., 36, 128
Gardeners Chronicle, 11, 128
Gardiner, J. G., 10, 20, 129
Gardner, R., 45, 129
Garman, W. H., 111, 124
Garner, W. W., 32, 33, 35, 40, 72, 74, 75, 83, 90, 129
Gassner, G., 11, 85, 129
Gast, P. R., 57, 98, 103, 106, 109, 129
Gauch, H. G., 70, 72, 129
van Geluwe, J., 121
Gerdel, R. W., 9, 155
Gerlach, —., 7, 129
Gilbert, B. E., 7, 33, 43, 70, 77-80, 84, 85, 89, 98, 116, 129
Gilbert, C. S., 120
Gilbert, J. H., 7, 137
Gildehaus, E. J., 70, 129
Gile, P. L., 21, 129
Gilligan, G. M., 42, 129
van Ginneken, P. J. H., 91, 103, 129
Ginsburg, S., 85, 134
Glasscock, H. H., 30, 129
Glenister, P. R., 75, 129
Godlewski, E., 15, 71, 97, 109, 110, 129
Goeze, G., 11, 85, 129
Goodall, D. W., 16, 22, 65, 67, 69, 70, 81, 87, 89, 114, 120, 129, 130
Gortner, R. A., 133
Gossard, A. C., 68, 91, 130
Gourley, J. H., 42, 155
Greaves, J. E., 42, 75, 132
Green, J., 112, 117, 130
Greenhill, A. W., 87, 130
Gregory, F. G., 48, 55, 56, 130
Greisenegger, —., 7, 130
Gribbins, M. F., 75, 112, 130
Grimmett, R. E. R., 26, 130
Gris, E., 8, 130
von Grünigen, F., 152
Guest, P. L., 8, 21, 112, 130
Gum, O. B., 71, 130
de Haan, I., 35, 75, 92, 130
de Haan, K., 75, 130
Haas, A. R. C., 10, 20, 24, 29, 30, 72, 73, 86, 114, 130, 146
Haddock, J. L., 16, 130
Haessner, —., 13, 130
Hageman, R. H., 132
Halais, P., 42, 85, 104, 105, 113, 114, 131
Hale, J. B., 87, 94, 131

Haley, D. E., 130
Hall, A. D., 16, 60, 71, 76, 94, 131
Haller, M. H., 70, 114, 119
Hambidge, G., 10, 11, 38, 39, 69, 74, 77, 78, 131
Hammar, H. E., 87, 102, 118
Hanamann, J., 15, 60, 131
Hance, F. E., 64, 67, 69, 79, 89, 91, 104, 112, 113, 131, 143, 155
Hansen, C. J., 29, 131
Hardin, L. J., 43, 70, 85, 129
Hardy, F., 25, 38, 60, 69, 92, 99, 109, 117, 131
Harley, C. P., 21, 81, 89, 91, 138
Harper, H. J., 112, 125
Harrington, J. F., 68, 89, 131
Hart, M. L. T., 17, 131
Hartman, J. D., 132
Haselhoff, E., 17, 131
Heinicke, A. J., 23, 131
Heinrich, R., 12, 13, 57, 58, 67, 68, 94, 131
Hellriegel, —., 12, 131
Helmkampf, A., 13-15, 57, 59, 76, 80, 96, 131
Herschler, A., 20, 110, 111, 131
Hester, J. B., 8, 40, 43, 84, 87, 93, 106, 112, 123, 131
Hibbard, P. L., 123
Hibon, J., 41, 113, 132
Hilgeman, R. H., 42, 77, 91, 132
Hill, H., 10, 22, 23, 25, 30, 38, 39, 43, 87, 90, 92, 98, 132
Hirschberger, W., 9, 143
Hirst, C. T., 42, 75, 132
Hoagland, D. R., 79, 89, 106, 114, 123, 132
Hodgkiss, 40, 132
Hoffer, G. N., 10, 42, 82, 93, 132
Hoffmann, M., 17, 99, 101, 106, 132
Hoffman, N. W., 8, 11, 118
Holmes, R. L., 105, 132
Hood, S. L., 81, 132, 144
Huggins, W. C., 138
Hughes, A. E., 26, 119
Hunter, A. S., 100, 107, 111, 132
Hunter, J. G., 20, 35, 125, 132
Hurwitz, C., 132, 144

Iljin, W. S., 21, 91, 132
Ingalls, R. A., 65, 132
Ingram, J. M., 42, 43, 132
van Itallie, T. B., 17, 26, 29, 33, 36, 39, 94, 95, 99, 132, 133

Jacob, A., 41, 82, 126, 133
Jacobson, H. G. M., 35, 133
Jacobson, L., 81, 87
Jakuškin, I., 16, 106, 133
Janssen, G., 72, 119
Januszewski, Z., 14, 133
Jefferiss, A., 133
Jessen, W., 150
John, J. L., 125
Johns, H. K., 150
Johnson, L. H., 85, 133
Johnston, F. B., 10, 22, 23, 87, 92, 132
Jones, H. A., 39
Jones, H. E., 29, 35, 39, 40, 43, 109, 133
Jones, J. O., 22, 32, 42, 45, 76-79, 106, 133, 145, 154
Jones, J. P., 10, 28, 133
Jones, W. N., 89, 133
Jones, W. W., 67, 99, 133
Jornlin, D. F., 144
Joulie, H., 15, 58, 133

Kalin, E. W., 35, 133
Kauter, A., 17, 133
Keiller, P. A., 89, 133
Kelley, W. P., 28, 30, 36, 133
Kelly, J. B., 149
Kenworthy, A. L., 10, 20, 36, 126
Kezer, A., 149
Kidson, E. B., 22, 42, 69, 70, 77, 89, 133, 134
Kinnison, A. F., 8, 31, 73, 128
Klemen, R., 42, 134
Knudson, 85, 134
von Kolnitz, H., 146
Kooper, W. D., 65, 144
Kosceleckiĭ, A., 9, 134
Kosutany, T., 65, 134
Krantz, B. A., 148
Kretschmer, —., 137
Kriel, H. T., 109, 134
Krüger, 82, 134
Kubota, T., 104, 105, 113, 124

Lagatu, H., 35, 41, 42, 59, 67, 80, 110, 111, 114, 116, 134-136, 146
Lakin, H. W., 122
Lange, W., 18, 136
Large, E. C., 26, 32, 117, 137
Larsen, O. H., 11, 123
Larson, C. A., 69, 137
Lavin, G. I., 10, 20, 89, 149
Lawes, J. B., 7, 137
Lazo, F., 42, 88, 107, 110, 120
Lazurskiĭ, A. V., 11, 137
Lee, H. A., 34, 137
Leeper, G. W., 82, 137
Lemesle, —., 42, 153
Levitt, E. C., 27, 30, 137
Liebich, H., 87, 137
Liebig, G. F., Jr., 72, 73, 123, 137
von Liebig, J., 7, 12, 47, 58, 59, 96, 137
Liebscher, —., 15, 18, 100, 101, 116, 137
Liechti, P., 17, 99, 137, 138
Lilleland, O., 23, 26, 31, 32, 36, 42, 43, 45, 66, 67, 73, 78, 101, 112, 114, 116, 127, 137
Lindner, R. C., 21, 31, 39, 80, 81, 89, 91, 115, 117, 138
Lindstrom, H. V., 133
Lineberry, R. A., 10, 33, 34, 69, 74, 86, 114, 138
Loehwing, W. F., 21, 116, 138
Löhnis, M. P., 30, 138
Lorenz, O. A., 70, 71, 74, 87, 90, 102, 138
Lott, R. V., 73, 138
Lowry, M. W., 83, 88, 138
Lüdecke, H., 134
Lundegårdh, H., 29, 44, 57, 58, 66, 68, 87-90, 93, 100, 101, 107, 109, 113-116, 138
Lutman, B. F., 72, 138
Lyman, C., 32, 73, 89, 139
Lyon, C. B., 35, 36, 75, 139

McCallum, R. D., 126
McCollam, M. E., 66, 67, 77-79, 101, 116, 139
McCool, M. M., 65, 71, 75, 76, 85, 139
McDonald, J. A., 7, 77, 90, 92, 98, 109, 110, 131, 139
McGeorge, W. T., 27, 69, 139
MacGillivray, J. H., 84, 117, 139
McHargue, J. S., 34, 132, 137
Mack, W. B., 41, 63, 67, 76, 78-80, 91, 151
McKibbin, R. R., 82, 149
McLarty, H. R., 23, 28, 139
McLean, F. T., 129
McMurtrey, J. E., Jr., 40, 129, 139
McNaught, K. J., 44, 139

MacVicar, R., 114, 123, 139
Macy, P., 57, 58, 94, 96, 97, 100, 106, 139
Magistad, O. C., 139
Magness, J. R., 42, 45, 77, 79, 97, 113, 119, 125, 139
Maier, W., 25, 26, 33, 71, 139
Majewski, F., 147
Mann, C. E. T., 21, 81, 92, 140, 154
Manshard, E., 111, 140
Marsh, A. W., 71, 98, 140
Marsh, R. P., 28, 86, 140
Martin, J. C., 106, 132
Martin, J. F., 124
Martin, W. E., 42, 78, 91, 140
Maschhaupt, J. G., 71, 73, 76, 140
Maskell, E. J., 48
Mason, T. G., 65, 71, 83-86, 140, 145
Mather, T. H., 84, 140
Maume, L., 35, 41, 42, 59, 67, 80, 110, 111, 113, 114, 117, 135, 136, 140, 141, 146
Maunsell, P. W., 89, 141
Maurmann, G., 150
Mayhugh, 126
Mayr, C., 17, 141
Mehlich, A., 9, 10, 141
Menchikowsky, F., 110, 141
Merkle, F. G., 8, 141
v.d. Merwe, A. D., 141
Methley, W. J., 118
Metz, —., 74, 141
Meyer, J., 148
Milad, Y., 21, 141
Millar, C. E., 85, 109, 111, 124, 139
Miller, J. T., 122
Millikan, C. R., 27, 141
Minges, P. A., 83, 87, 138
Minina, E. G., 147
Mitchell, H. L., 11, 45, 57, 58, 65, 94, 97, 103, 105, 106, 112, 116, 141
Mitscherlich, E. A., 7, 9, 18, 47, 48, 141, 142
Moir, W. W. G., 44, 142
Morgan, E. T., 45, 74, 150
Morgan, M. F., 8, 9, 43, 87, 89, 142
Moriguchi, S., 44, 68, 124
Morris, A. A., 20, 30, 73, 142
Morris, H. D., 73, 124
Morris, V. H., 155
Moser, F., 42, 142
Moss, E. G., 129
Moxon, A. L., 144
Muckenhirn, R. J., 73, 74, 142
Muhr, G. R., 40, 71, 72, 74, 75, 103, 109, 111, 142
Mulder, E. G., 9, 142
Müller, F., 11, 17, 142
Münter, F., 18, 60, 70, 75, 90, 103, 107, 109-111, 113, 115, 142

Nanninga, A. W., 15, 142
Nash, L. B., 92, 149
Nasharty, A. H., 67, 142
Neeb, G. A., 82, 142
Neller, J. R., 42, 71, 76, 84, 85, 114, 142
Nemec, A., 32, 42, 142
Neubauer, H., 7, 9, 142, 143
New Jersey Agricultural Experiment Station, 74, 143
New Zealand Department of Scientific and Industrial Research, 45, 70, 89, 143
Nicholas, D. J. D., 22, 32, 76-80, 133, 143, 145
Nicholson, M. N., 10
Nicholson, R. I., 27, 30, 137
Nicol, H., 9, 143
Nightingale, G. T., 10, 43, 58, 65, 67-69, 84, 86, 91, 102, 143
Niklas, H., 9, 143
Nishimura, T., 69, 89, 143
Noble, W. M., 8, 118
Nolte, O., 60, 143

Oertel, A. C., 40, 149
von Ohlen, F., 139
Ohlrogge, A. J., 42, 143, 148
Olsen, C., 21, 72, 143
Olson, L. C., 42, 117, 143
Olson, O. E., 44, 144
Opitz, K., 73, 144
Oserkowsky, J., 21, 31, 87, 88, 110, 144
Osmond, D. A., 25, 38, 42, 114, 154
Otto, R., 65, 144

van der Paauw, F., 17, 131
Page, N. R., 65, 68, 86, 89, 101, 122, 144
Painter, J. H., 20, 36, 40, 69, 126, 144
Parbery, N. H., 20, 25, 27, 30, 69, 144
Parker, E. R., 123
Parks, R. Q., 89, 132, 144
Parsche, F., 8, 144
Patry, L. M., 119
Peech, M., 89, 97, 121, 144
Pember, F. R., 7, 129
Penston, N. L., 65, 144
Percival, G. P., 77, 87, 145
Petersen, P., 101, 144
Peterson, W. H., 84, 144
Petrie, A. H. K., 83, 144
Pettinger, N. A., 28, 42, 43, 82, 84, 85, 100, 144
Pfeiffer, T., 17, 18, 57, 62, 70, 100, 112, 144, 145
Pfützer, G., 84, 145
Phillis, E., 65, 71, 83-86, 140, 145
Pierre, W. H., 45, 84, 88, 110, 121, 145, 149
Pigorini, L., 65, 145
Piper, C. S., 8, 10, 29, 39, 45, 59, 80, 82, 89, 113, 145, 148
Plant, W., 32, 42, 45, 78, 87, 89, 133, 145, 154
Poehlman, J. M., 84, 85, 114, 145
Pohlman, G. G., 45, 84, 88, 145
Poschenrieder, H., 143
Potter, G. F., 77, 87, 145
Powers, W. L., 28, 38, 39, 75, 98, 100, 124, 126, 140
Prince, A. L., 100, 111, 119, 146
Proebsting, E. L., 73, 74, 154
Puffeles, M., 110
Purvis, E. R., 8, 146

Quiñones, P. E., 20, 146

Rademacher, B., 11, 29, 113, 146
Rahn, E. M., 152
Raleigh, G. J., 139
Raleigh, S. M., 75, 146
Rathmann, W., 145
Raum, H., 17, 146
Ravaz, —., 21, 146
Ravikovitch, S., 27, 114, 146
Rayner, D. S., 123
Reed, H. S., 29, 30, 146
Reeve, E., 10, 28, 35, 146
Regeimbal, L. O., 139
Reid, J. J., 130
Remington, R. E., 44, 146
Remy, T., 16, 17, 41, 68, 94, 95, 146

Reuther, W., 22, 31, 32, 38, 42, 69, 77, 121, 128, 131, 146
Reynolds, E. B., 128
Rhode Island Agricultural Experiment Station, 83, 97, 98, 112, 146
Richards, F. J., 10, 69, 81, 83, 107, 112, 146, 147
Riches, J. P., 89, 147
Rieman, G. H., 139
Rigg, T., 36, 147
Rippel, A., 145
Ritter, E., 17, 99, 137
Roach, W. A., 8, 11, 20, 21, 69, 81, 82, 89, 114, 147
Robbins, W. R., 143
Roberts, W. O., 8, 20, 116, 147
Robertson, D. W., 45, 129, 149
Robinson, W. O., 44, 45, 64, 147
Rodriguez, G., 90, 92, 99, 109, 110, 131, 139
Roth, H., 84, 145
Roy, W. R., 27, 147
Russell, R. D., 45, 133

Sabinin, D. A., 88, 147
Sackett, W. G., 149
Salter, R. M., 66, 82, 147
Samuel, G., 29, 39, 148
Sandrock, W., 42, 79, 148
Sartory, A., 9, 148
Sartory, R., 148
Sayre, C. B., 116, 148
Scarseth, G. D., 29, 35, 39, 40, 43, 58, 65, 70, 75, 87, 109, 111, 116, 117, 125, 126, 133, 148
Scheffer, F., 10, 125
Schermerhorn, L. G., 143
Schneider, P., 16, 72, 148
Schneider, W., 9, 143
Schober, K., 9, 148
Scholz, W., 21, 148
Schoorel, A. F., 35, 92, 130
Schottmüller, A., 143
van Schreven, D. A., 75, 81, 94, 148
Schulze, B., 65, 148
Schuster, C. E., 7, 10, 148
Schütz, J., 65, 148
Scofield, C. S., 26-28, 30, 36, 75, 117, 148
Scott, D. H., 125
Scott, L. E., 27, 113, 148
Scurti, F., 10, 148
von Seelhorst, —., 15, 137
Seidel, F., 9, 148
Sekera, F., 9, 148
Sen, A. T., 33, 40, 74, 89, 148, 149
Shaw, J. K., 42, 43, 77, 149
Shaw, W. M., 118
Shear, G. M., 10, 20, 89, 149
Shedd, O. N., 85, 149
Shelton, F. A., 131
Shepherd, J. B., 155
Shigeura, —., 124
Shive, J. W., 28, 33, 35, 40, 65, 74, 86, 87, 108, 132, 140, 146, 149
Sieling, D. H., 126
Simakova, T., 9, 149
Simmermacher, W., 145
Sjollema, B., 36, 44, 149
Skinner, W. W., 89, 149
Smith, C. T., 42, 77, 149
Smith, J. B., 43, 98, 116, 129
Smith, J. G., 132
Smith, M. E., 86, 149
Smith, O., 92, 149
Smith, S.E., 44, 120
Smock, R. M., 42, 77, 149
Snell, J. F., 82, 149
Snell, M. E., 74, 112, 120
Söding, H., 9, 120
Somers, I. I., 33, 40, 74, 86, 87, 108, 149
Soulmagnon, M., 113, 149
Southwick, L., 22, 38, 42, 69, 77, 149
Spencer, E. L., 10, 20, 89, 149
Spurway, C. H., 8, 88, 149
Stahl-Schröder, M., 13-15, 64, 66, 70, 73, 80, 109, 113, 149
Stair, E. C., 132
Stanford, G., 28, 39, 108, 110, 149
Steckel, J. E., 43, 149
Stephens, C. G., 40, 149
Stephenson, R. E., 7, 10, 148
Stewart, L. C., 149
Stewart, R., 7, 149
Stokes, W. E., 25, 120
Stout, P. R., 132
Stutzer, A., 17, 150
Süchting, H., 9, 59, 150
Suzuki, U., 65, 150
Swanback, T. R., 35, 133

Tabor, P., 88, 138
Tacke, B., 17, 150
Tam, R. K., 44, 79, 150
Tanada, T., 34, 71, 73, 75, 125, 150
Teakle, L. J. H., 16, 20, 27, 29, 45, 64, 66, 74, 96, 97, 99, 101-103, 106, 150
Templeman, W. G., 83, 147
Thoday, D., 91, 150
Thomas, H. E., 144
Thomas, I., 16, 45, 64, 66, 150
Thomas, W., 41, 42, 58, 63, 67, 76, 78-80, 91, 109, 113-115, 150-152
Thompson, S. G., 147
Thomson, R. H. K., 23, 45, 68, 97, 118, 119, 123
Thorne, D. W., 21, 85, 87, 91, 152
Thornton, S. F., 9, 42, 43, 58, 76-80, 82, 84, 85, 116, 144, 152
Throssell, G. L., 150
Thut, H., 139
Tokuoka, M., 74, 152
Tollens, B., 112, 152
Toth, S. J., 132
Tottingham, W. E., 123, 139
Trelease, H. M., 97, 152
Trelease, S. F., 97, 152
Trischler, J., 143
Trost, J. F., 82, 132
Trubeckova, O. M., 147
Truffaut, G., 9, 152
Trumble, H. C., 7, 128
Truninger, E., 17, 71-75, 152
Truog, E., 11, 77, 89, 120, 141
Tryon, H. H., 45, 128
Turton, A. G., 16, 45, 64, 66, 74, 96, 101, 103, 150
Tysdal, H. M., 155

Ulrich, A., 11, 37, 43, 45, 58, 64, 68, 72, 96, 98, 103, 113, 152
Ussery, H. D., 10, 20, 89, 149

Vaidya, V. G., 152
Vanselow, A. P., 36, 89, 123, 137, 152

Veale, P. T., 45, 152
Vinall, H. N., 83, 153
Vinet, E., 42, 109, 153
Vittum, M. T., 42, 153
Vorbuchner, —., 7, 130
de Vries, O., 37, 153

Wadleigh, C. H., 70, 72, 83, 84, 129, 153
Wagner, F., 42, 72, 153
Wagner, P., 16, 17, 62, 70-72, 74-76, 97-100, 102, 103, 106, 153
Wain, R. L., 30, 129
Walbridge, N. L., 72, 138
Walkley, A., 89, 145
Wall, M. E., 35, 75, 89, 153
Wallace, A., 21, 85, 87, 91, 152
Wallace, T., 10, 20-23, 25, 27, 32, 38, 42, 58, 69, 70, 72-74, 76, 81, 90, 92, 113-116, 133, 140, 154
Wallihan, E. F., 68, 69, 154
Walsh, T., 11, 36, 43, 87, 114, 128, 154
Waltman, C. S., 42, 78, 154
Wander, I. W., 42, 155
Wann, F. B., 21, 38, 39, 118, 155
Wark, D. C., 43, 84, 112, 113, 155
Warne, L. G. G., 69, 155
Watson, D. J., 113, 155
Watts, V. M., 119
Waugh, J. G., 30, 31, 42, 45, 78, 125, 155
Weinhold, A., 12, 155
Weldon, M. D., 71, 75, 76, 85, 139
Welton, F. A., 82, 155
Wiegner, G., 17, 95, 99, 155
Wiessmann, —., 7, 155
Wilcox, J. C., 139
Wilcox, L. V., 26-28, 30, 36, 117, 148
Wilfarth, —., 9, 155
Wilkins, H. L., 83, 153
Williams, K. T., 122
Williams, W. R. L., 23, 24, 119
Wilms, J., 137
Wimmer, G., 134
Winogradsky, S., 9, 155
Wolf, B., 56, 71, 78, 87, 89, 99, 115, 155
Wolff, E., 12, 17, 100, 101, 155
Woodbridge, C. G., 23, 24, 128, 139, 155
Woodward, T. E., 65, 155
Wright, C. H., 8, 155
Wright, L. E., 70, 119, 127

Yates, F., 113, 114, 155
Yuen, Q. H., 64, 67, 69, 91, 104, 112, 113, 155

MADE AND PRINTED IN GREAT BRITAIN BY
THE CAMBRIAN NEWS (ABERYSTWYTH), LTD.,
ABERYSTWYTH.

# PUBLICATIONS

## TECHNICAL COMMUNICATIONS ON RELATED SUBJECTS

16. Further Work on Plant Injection for Diagnostic and Curative Purposes. 1945. *W. A. Roach and W. O. Roberts.* 1/6.

---

## OTHER TECHNICAL COMMUNICATIONS AVAILABLE

2. Field Experiments in Horticulture. 1931. *T. N. Hoblyn.* 2/-.

4. Problems of Fruit Tree Nutrition. 1933. *T. Wallace.* 2/-.

5. The "Degeneration" of the Strawberry. 1934. *D. Akenhead, R. V. Harris, G. H. Berkeley, A. M. Massee.* 2/-.

6. The Nutrition and Manuring of Soft Fruits. 1936. *T. Wallace.* 2/-.

9. A Review of the literature on Stock-scion Incompatibility in Fruit Trees, with Particular Reference to Pome and Stone Fruits. 1937. *G. K. Argles.* 5/-.

12. Plant Hormones and their Practical Importance in Horticulture. 1939. *H. L. Pearse.* 3/6.

13. Vegetative Propagation of Tropical and Sub-Tropical Plantation Crops. 1940. *G. St. Clair Feilden and R. J. Garner.* 3/6.

14. Propagation by Cuttings and Layers. Recent Work and its Application, with Special Reference to Pome and Stone Fruits. 1944. *R. J. Garner.* 3/6.

15. Spring Frost Damage in Orchards and its possible prevention. 1945. 1/6.

18. Fruit Fall and its Control by Synthetic Growth Substances. *M. C. Vyvyan.* 1946. 3/6.

---

## HORTICULTURAL ABSTRACTS

A quarterly journal issued since 1931, covering world literature on all aspects of horticulture, including fruit, vegetables, commercial flower production, the cultivation of tropical plantation crops and the storage and processing of horticultural products.

Price 25/- a volume of four numbers, single copies 7/6. Concession price to subscribers ordering direct in Great Britain or other countries of the British Commonwealth of Nations 20/- a volume.

## SUBJECT AND AUTHOR INDEX TO HORTICULTURAL ABSTRACTS,

Volumes I-X, 1931-1940, 25s.; volumes XI-XV, 1941-1945 in preparation.